Gümüşhane University Journal of Science

GUFBD / *GUJS* (2023) 13(3): 616-631 doi: 10.17714/gumusfenbil.1274987 Research Article

Investigation of changes in geomechanical properties of sandstones under different saturation and anisotropy conditions: Example from Gümüşhane (NE Türkiye)

Farklı doygunluk ve anizotropi koşullarında kumtaşlarının jeomekanik özelliklerindeki değişimlerin incelenmesi: Gümüşhane örneği (KD Türkiye)

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• Received: 31.03.2023 • Accepted: 27.05.2023

Abstract

In this study, the changes in various geomechanical properties were studied for sandstones cropped out at the Mescitli region of the Gümüşhane city under different saturation and anisotropy conditions. For this purpose, 225 specimens were prepared considering the lamination planes of those were chosen to have orientation of 0, 30, 45, 60 and 90° relative to loading direction. Index properties of the sandstones such as dry unit weight (γ_{dry}), saturated unit weight (γ_{sat}), water absorption by weight (A_w) and water absorption by volume (A_v) were assigned. In accordance with the objective of study P wave velocity, uniaxial compressive strength and indirect tensile strength values were determined based on different saturation and anisotropy conditions. It was noted as a result of the observations carried out that specimens parallel to lamination have higher wave velocities in general when compared with specimens that are perpendicular to lamination planes. While uniaxial compressive strength values for sandstones are high for specimens which are parallel and perpendicular to lamination, the lowest strength value was observed in specimens with an anisotropy angle of 30°. In addition, it was also observed that the strength values decrease at a significant level with increasing saturation conditions. Strength anisotropy ratio (R_{UCS}) for sandstones varies between 1.28–1.49 based on different saturation conditions. Similarly, while indirect tensile strength values were higher in specimens that were parallel and perpendicular to lamination, they were lower for other anisotropy orientations. Indirect tensile strength values also decreased with increasing degree of saturation.

Keywords: Anisotropy, Degree of saturation, Geomechanical properties, Lamination, Sandstone

Öz

Bu çalışmada Gümüşhane ili Mescitli yöresinde yüzeylenen kumtaşlarının değişik doygunluk ve anizotropi şartlarında jeomekanik özelliklerindeki değişimler araştırılmıştır. Bu amaçla laminalanma düzlemleri esas alınarak yükleme yönü ile 0, 30, 45, 60 ve 90° yapacak şekilde farklı anizotropi açılarında konumlanmış 225 adet numune hazırlanmıştır. Kumtaşı örneklerinin kuru birim hacim ağırlık (γ_{dry}), doygun birim hacim ağırlık (γ_{sat}), ağırlıkça su emme (A_w) ve hacimce su emme (A_v) gibi indeks özellikleri tayin edilmiştir. Çalışma amacına uygun olarak kumtaşlarının değişen doygunluk ve anizotropi koşulları esas alınarak P dalga hızı gibi fiziksel özellikleri ile tek eksenli basınç ve dolaylı çekilme dayanımları belirlenmiştir. Yapılan değerlendirmeler sonucunda genel olarak laminalanmaya paralel örneklerin laminalanmaya dik olan örneklere göre daha yüksek dalga hızı değerine sahip oldukları gözlemlenmiştir. Kumtaşlarında tek eksenli basınç dayanımı değerleri laminalanmaya paralel ve dik olan örneklerde yüksek değerler gösterirken en düşük dayanım değeri 30^o anizotropi açısına sahip örneklerden elde edilmiştir. Ayrıca artan doygunluk koşulları ile dayanım değerinin önemli miktarda azaldığı gözlemlenmiştir. Farklı doygunluk koşullarına bağlı olarak kumtaşlarının dayanım anizotropi oranı (R_{UCS}) 1.28-1.49 arasında değişim sunmaktadır. Dolaylı çekilme dayanımı değerleri benzer şekilde laminalanmaya paralel ve dik örneklerde yüksek iken diğer anizotropi açılarında ise düşüktür. Dolaylı çekilme dayanımı değerleri de doygunluk derecesindeki artışa bağlı olarak azalım göstermektedir.

***Anahtar Kelimeler**: Anizotropi, Doygunluk derecesi, Jeomekanik özellikler, Laminalanma, Kumtaşı*

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ISSN: 2146-538X e-ISSN: 2146-538X https://dergipark.org.tr/tr/pub/gumusfenbil

1. Introduction

Rock environments are defined as those which are anisotropic, discontinuous and heterogeneous. Both the strength and deformation characteristics of rocks vary according to anisotropy due to the orientation of the minerals and/or orientation of the grains that form the rock and the effect of discontinuities. Depending on the stresses that the rocks are affected from, anisotropy is observed in metamorphic rocks as foliation, in sedimentary rocks as fine layers via lamination and in magmatic rocks as mineral arrangement by way of flow (Amedei, 1996). It is important to define strength and deformation of specimens oriented at different angles according to anisotropy planes considering the effect of anisotropy.

Just like anisotropy, different saturation conditions may also cause changes in the behavior of rocks. Dry rock specimens with zero degree of saturation are mostly used in experimental studies carried out in the laboratory. Both the strength and deformation characteristics of the rock material are determined according to this condition. However, the rock is not always dry in its natural environment and may have different degrees of saturation. As a result, rocks may actually display different strengths based on the varying saturation conditions. The rock type selected is also very important for putting forth the impact of saturation conditions on rock behavior. Sedimentary rock types that are suited more to saturation should be preferred instead of magmatic and metamorphic rocks since rock types with low porosity and unconnected void will not be suited for saturation.

The number of studies which examine the relationships between the physical– mechanical characteristics of rocks is quite high in literature (Chang et al., 2006; He, 2006; Franzini et al., 2007; Lezzerini et al., 2008; Singh & Sharma, 2008; Jianhong et al., 2009; Moradian & Behnia, 2009; Ji & Marcotte, 2009; Gürocak et al., 2012; Onur et al., 2012; Chen et al., 2015; Karaman et al., 2015b; Kaya & Karaman, 2016; Columbu et al., 2017; Wang et al., 2017; Yin et al., 2018; Buosi et al., 2018). However, there are also studies which examine the impact of anisotropy on rock behavior (e.g. Donath, 1964; Batugin & Nirenburg, 1972; Behrestaghi et al., 1996; Çolak, 1998; Ajalloeian & Lahskaripour, 2000; Chen & Hsu, 2001; Garagon, 2007; Tavallali & Vervoort, 2010; Cho et al., 2012; Yücel, 2012; Tavallali & Vervoort, 2013; Gökçe, 2015; Singh et al., 2015; Kim et al., 2016; Lin et al., 2017; Kundu et al., 2018; Li et al., 2020) along with studies which examine different saturation conditions of rocks and the impact of these conditions on rock behavior (e.g. Helle et al., 2003; He, 2006; Chang et al., 2006; Kahraman, 2007; Török & Vásárhelyi, 2010; Karakul & Ulusay, 2013). It was observed that the highest uniaxial compressive strength (UCS) is generally obtained at anisotropy orientations of 0 and 90°, whereas the lowest UCS is generally obtained at anisotropy orientation of 30° (Ramamurthy, 1993).

Donath (1964), carried out experimental studies on specimens with anisotropy orientations of 0, 15, 30, 45, 60, 75 and 90° on slates with well–developed planar foliations that the highest compressive strength was obtained for the specimen on which stress was applied perpendicular to the foliation plane (90°). Ajalloeian and Lahskaripour (2000), conducted studies regarding to the strength anisotropy of siltyshales and mudshales. Maximum compressive strength value was measured for β=90°. Both siltshale and mudshale exhibited minimum compressive strength in the direction β=30°. Cho et al. (2012), worked on a series of experimental studies for examining the deformation and strength anisotropy of gneiss, shale and schist-type metamorphic rocks. It was put forth as a result of the study that anisotropy is effective on deformation and strength and that anisotropy should be taken into consideration with regard to engineering applications. Singh et al. (2015), carried out a triaxial compressive test on phyllite, slate and orthoquartzites and compared to the behavior of these rocks with the results of other studies in the literature. It was determined that the specimens with an anisotropy orientation of 90° (perpendicular to the direction of compression load) had higher strength in comparison with the specimens which have 0° (parallel to the direction of compression load) angle.

It was emphasized in studies by He (2006), on degrees of saturation that conditions such as pore pressure and water saturation may have an impact on the wave velocity of the rock. P and S wave velocities were measured on dry and saturated conglomerates with low porosity and it was observed that the P wave velocity increased in saturated specimens in comparison with dry specimens. Török and Vásárhelyi (2010), carried out studies on travertines examining whether there is any empirical relationship between physical–mechanical properties such as porosity, density, P wave velocity and UCS under dry and saturated conditions. They were determined that UCS and ultrasonic pulse velocity; effective porosity and ultrasonic pulse velocity were exponentially related to. Also, test results presented in the study indicate that there was a difference in the physical properties of travertine displaying various fabric. In this respect, Karakul and Ulusay (2013), examined the relationships between the strength parameters of rocks and P wave velocities under different saturation conditions. A total of 14 different rock types were examined in the study in which measurement of P wave velocity at different saturations was used for estimating UCS and tensile strength values. It was observed as a result of the study that strength characteristics and elasticity modulus decreased based on saturation. In addition, it was also determined that the P wave velocity increased in some rock types and decreased in others depending on saturation.

It can be observed upon an examination of the studies in the literature that the anisotropic characteristics (e.g. lamination in sedimentary rocks or foliation in metamorphic rocks, etc.) together different saturation conditions play an important role on rock physical–mechanical behaviors. The number of studies in literature which evaluate these two instances is limited (Kumar, 2006; Kundu et al., 2018). Whereas anisotropy was taken as basis in both studies, degrees of saturation was taken into consideration only for dry and saturated conditions. In this study, the changes that may occur in the geomechanical properties of core specimens with different saturation conditions and different anisotropy orientations were investigated together. In addition, the effect of anisotropy and saturation on the rock strength properties were examined. A combined experiment was designed and conducted for studying rock formation. In this way, the integrated impact of changes in geomechanical properties for Mescitli (Gümüşhane, NE Turkey) sandstones were studied. Since there has not been a study in the literature which examines the integrated impact of both properties, in this respect, the study has a unique feature. Sandstones were preferred as rock types in the study since they contain lamination and due to the high porosity, they are more suited to saturation. Samples compiled from the late Cretaceous aged sandstones exposed to around the Gümüşhane city were used in the experimental studies. The lithologic unit that is also known as the Mescitli region sandstones cropped out both at the Mescitli village and its vicinity which is located in about 15 km northwest of the Gümüşhane city (Figure 1).

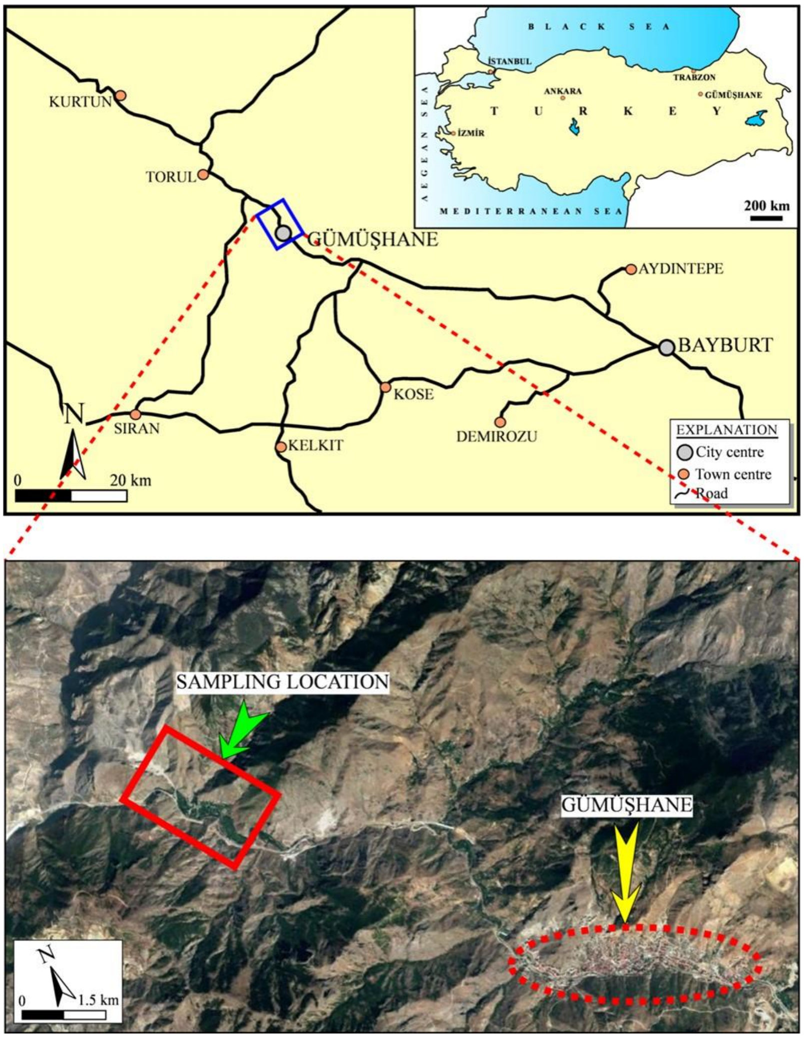

Figure 1. Location map of study area

2. Geology of the study area and its close vicinity

The Gümüşhane city and its close vicinity are located in the South Zone of the Eastern Pontide Tectonic Assembly (Ketin, 1966). In the region, lithologic units with ages varying from the Paleozoic to Quaternary with different lithologies are cropped out (Figure 2) (Güven, 1993).

Metamorphites that form the oldest basement rocks of the Gümüşhane region are cut by the early–late Carboniferous aged Gümüşhane Granitoid (Topuz et al., 2010). The unit that is typical with its large grain orthoclase is generally pink in color and contains abundant fractures and cracks depending on the tectonic events. These acidic magmatic intrusive rocks are unconformably overlain by the early–middle Jura aged Şenköy formation comprised of volcano–sedimentary sequence (Kandemir, 2004). Berdiga formation comprised of dolomite and dolomitic limestones with a wide surfacing area is conformably located on this sequence starting from late Jura (Pelin, 1977). Late Cretaceous-aged Kermutdere formation (Tokel, 1972) comprised of conglomerate, sandstone, limestone and marl alternation is conformably located on the Berdiga formation. The sandstones used in this study have been compiled from the Kermutdere formation that exposed to the Mescitli region. Eocene aged Alibaba formation is unconformably located on the Kermutdere formation and is comprised of andesite, basalt and their pyroclastites (Tokel, 1972). The formation can be easily discerned on the field with its dark gray color. Whereas the granitic rocks that cut all these units and surface on a narrow area form the Eocene aged granitic intrusions (Eyüboğlu et al., 2017). The youngest units in the region are Quaternary aged alluvium, terrace deposits and travertines.

The geological map of the study area and its vicinity is given in Figure 2.

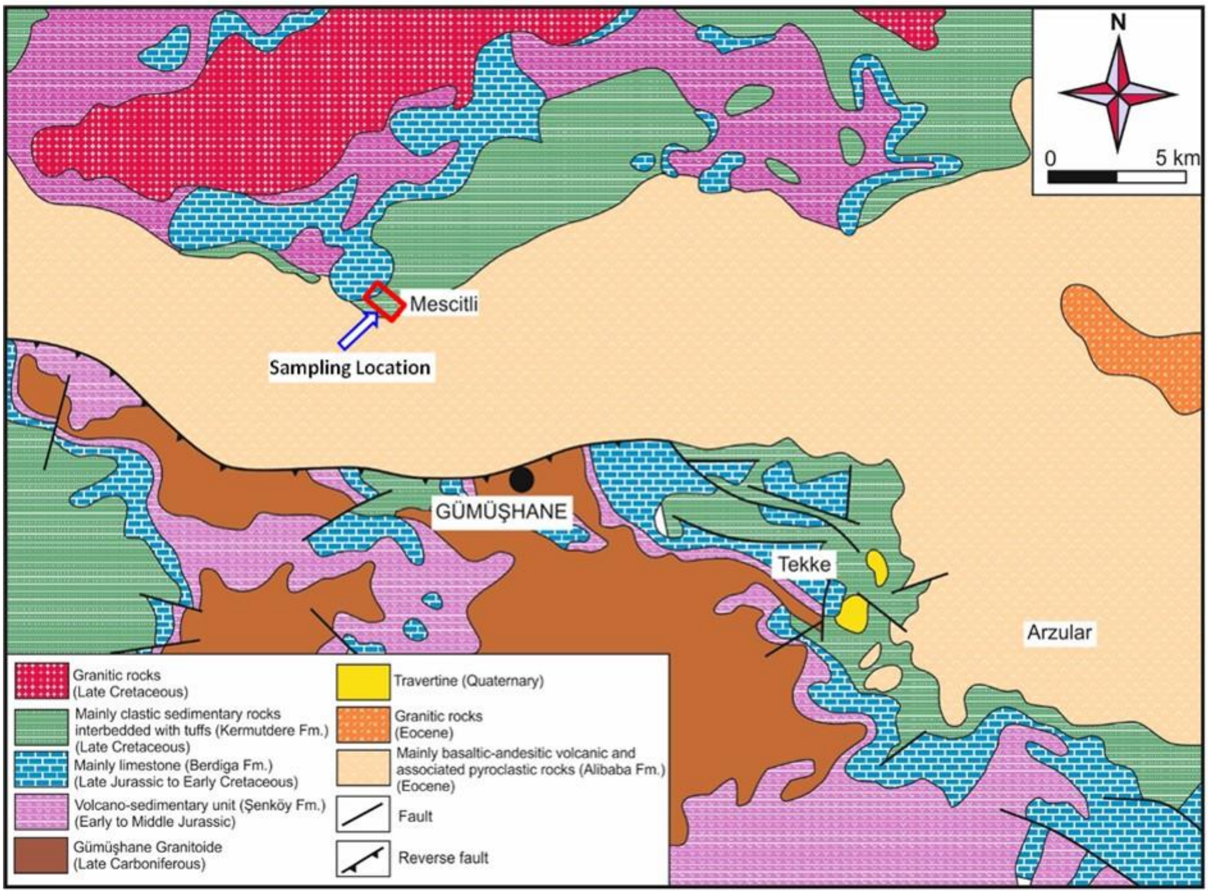

Figure 2. Geology map of the Gümüşhane city and its close vicinity (Modified from Güven, 1993)

3. Material and method

While the sandstone blocks were collected from the field, attention was given so that they were of the same thickness with the same lamination, grain size and hardened properties. Carrying out a detailed field study in the region, 11 blocks were sampled with dimensions of 20x30x40 cm.

Thin sections were prepared to represent each block to determine the mineralogical composition and grain size distribution of the samples. For grain size analysis, the size of the grains was measured along a line assumed to cross-section in two directions on a polarizing microscope. In order to determine the mineralogical composition of the sandstones, a modal analysis including 1000–point counts in each section was made using a polarizing microscope and point counter.

Afterwards, the directional core drilling machine was used in the laboratory to take cores from these blocks with diameters of NX (54 mm) in accordance with methods suggested by ISRM (2007).

Two different methods attract attention in literature for taking specimens while evaluating the anisotropy conditions. One of these is the method used by researchers such as Nasseri et al. (2003), Kumar (2006), Singh et al. (2015), in which anisotropy is evaluated by taking into consideration the angle (β) between discontinuity planes such as lamination, schistosity etc. and loading direction (Figure 3a). Another method is one used by researchers such as Zhang et al. (2010), Kim et al. (2016), for examining the impact of anisotropy on rock behavior by taking into account the perpendicular direction (θ) to the layering plane (Figure 3b).

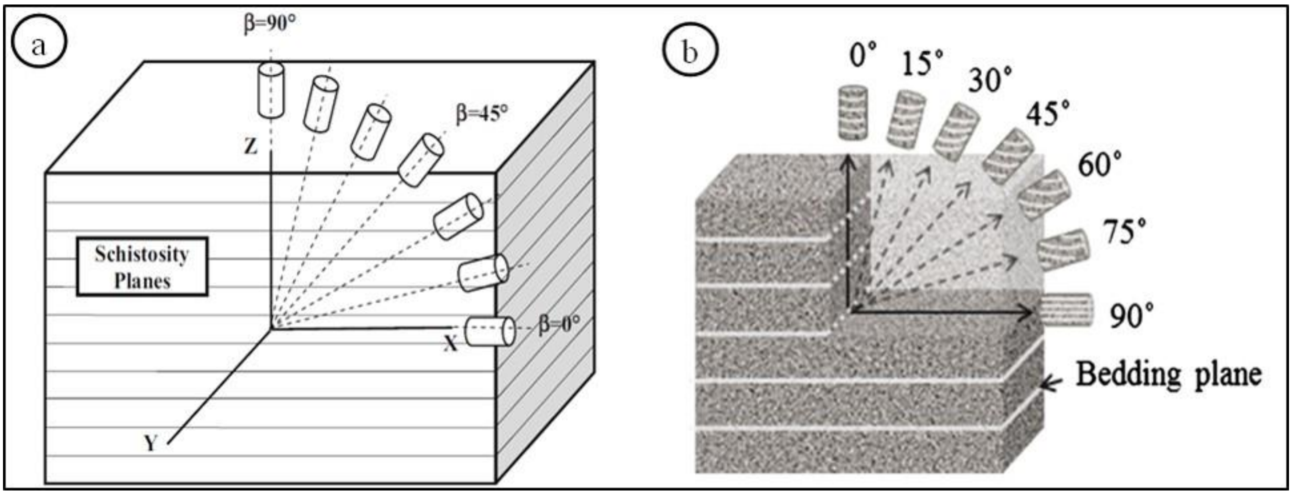

Figure 3. Evaluation of anisotropy according to (a) Kumar (2006) and (b) Kim et al. (2016), during sample preparation

In this study, the anisotropy is evaluated according to the method given in Figure 3a by considering the angle (β) between lamination planes and loading direction (Figure 4). The parallelism of the specimens with the lower and upper surfaces was controlled by way of a comparator watch with a sensitivity of 0.001 mm.

Figure 4. Core samples prepared according to the different anisotropy orientation (β) by taking into consideration the lamination planes

Core specimens with lengths of about 2.5–3 times their diameter, were used for the uniaxial compressive strength, whereas specimens with diameters that are about 2 times their length were prepared for the indirect (brazilian) tensile strength. A total of 75 sandstone samples were used for the UCS experiments, whereas a total of 150 specimens were used for the indirect tensile strength experiments. Methods suggested by ISRM (2007), were taken into account for determining the strength properties of sandstone samples.

To determine physical properties, the specimens were first dried at 105 ºC for 24 hours in a drying oven and then weighed to determine their dry masses. Afterwards, they were left to wait for 48 hours in distilled water and weighed to determine their saturated masses. Index properties of the specimens such as their unit weights, water absorption by weight and water absorption by volume were determined using these data. In addition, pycnometer tests were carried out so as to determine the specific gravity values for the rock specimens. Grain unit weights for the specimens (γ_s) were determined using the specific gravity values for each specimen. Porosity value of each specimen was calculated by way of Equation 1 given below which was also used in the previous studies (Heidari et al., 2013; Dag, 2018)

$$n = 1 - \frac{\gamma_{dry}}{\gamma_s} \quad (1)$$

Where n: total porosity (%), γ_{dry}: dry unit weight (kN/m^3) and γ_s: grain unit weight (kN/m^3).

In this study, experimental studies carried out by Dag (2018) were used to control water saturation with sandstone samples. Using the diagram in Figure 5, experiments and measurements were carried out on the specimens with the desired degree of saturation.

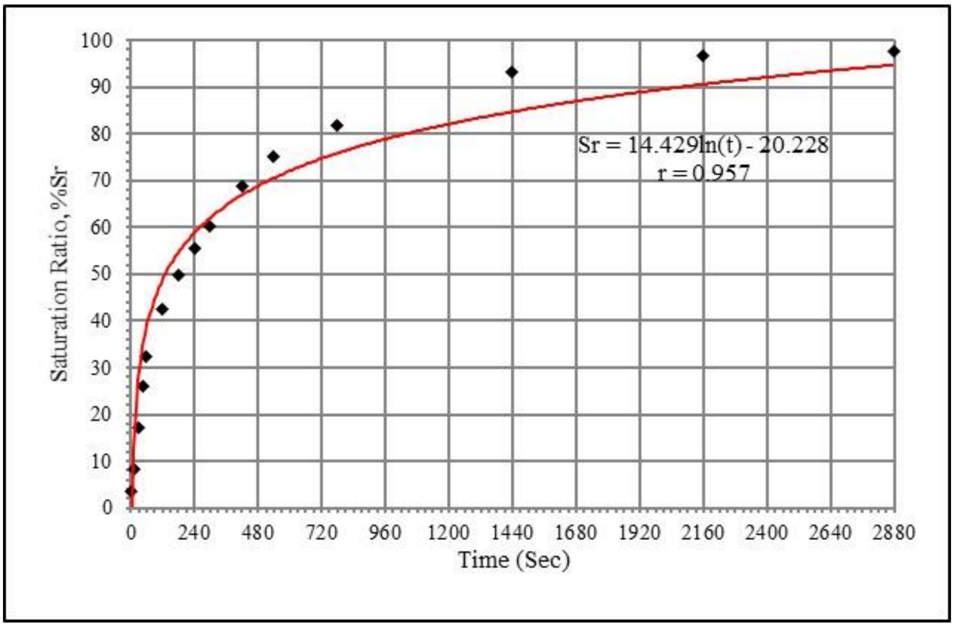

Figure 5. Change with time of the degree of saturation values for sandstone samples (Dag, 2018).

A total of 75 specimens were used for carrying out the ultrasonic velocity measurements of the rock material with 15 specimens having anisotropy orientations of (*β*) 0, 30, 45, 60 and 90°. From a total of 375 longitudinally wave velocity (V_p) each have been made on the sandstone specimens via ultrasonic wave experiments by taking into consideration the different degree of saturation (Sr %: 0, 25, 50, 75 and 100) and different anisotropy conditions.

4. Results

According to the grain size measurements, the grain size of the sandstone varies between 0.21–0.25 mm and it is determined that "medium sand" according to Wentworth size classification. As a result of the modal analysis, sandstones contain quartz, feldspar (alkali feldspar, plagioclase), rock fragments (volcanic and sedimentary), opaque mineral, secondary mineral (olivine, pyroxene, amphibole, epidote), matrix and cement (Table 1, Figure 6). According to the results of the modal analysis (Folk et al., 1970) sandstones were determined as lytic subarkose and lytic arkose.

Table 1. Modal analysis result of sandstone samples

Smp nu	Qu %	Feldspar %		Rock Fragment %		Matrix %	Cement %	Secondary Mineral %				Om %
		Af	Pl	Srf.	Vrf.			Ol	Amp	Pyr	Ep	
1	34.3	19	1.5	11.5	3.2	16.3	10.4	0	1.8	0.8	0	1.2
2	38.4	11.7	0.7	5.9	9.9	9.8	20.6	0	1.4	0.2	0	1.4
3	30.5	14.6	0.7	7.1	1.8	20.1	20.2	2.3	0.7	0	0.2	1.8
4	34.1	13	0.3	3.7	2.5	33	8.5	1.6	0.9	0	0	2.4
5	31.2	13.2	1	3.3	4.7	26	17	1.4	0	0	0	2.2
6	33.7	13.9	0.4	5.1	2.2	26.9	13.5	1.5	0.8	0	0.3	1.7
7	32.2	13.6	0.7	5.4	1.9	26.8	13.4	3.6	0.5	0	0	1.9
8	25.5	18.3	0	7.5	2.3	3.9	36.6	2.2	0.4	0	0.5	2.8
9	34.1	13.7	0.2	6	2.1	21.9	18.9	0.9	0.3	0.1	0	1.8
10	35.5	13.7	1.7	4.3	1.9	20.8	18.1	2.4	0.1	0	0	1.5
11	31.9	17.4	2.3	4.1	2.5	21	14.6	2.3	1.9	0.1	0	1.9

Smp nu: Sample number, Qu: Quartz, Af: Alcali feldspar, Pl: Plagioclase, Srf: Sedimentary rock fragment, Vrf: Volcanic rock fragment, Ol: Olivine, Amp: Amphibole, Pyr: Pyroxene, Ep: Epidotes, Om: Opaque mineral

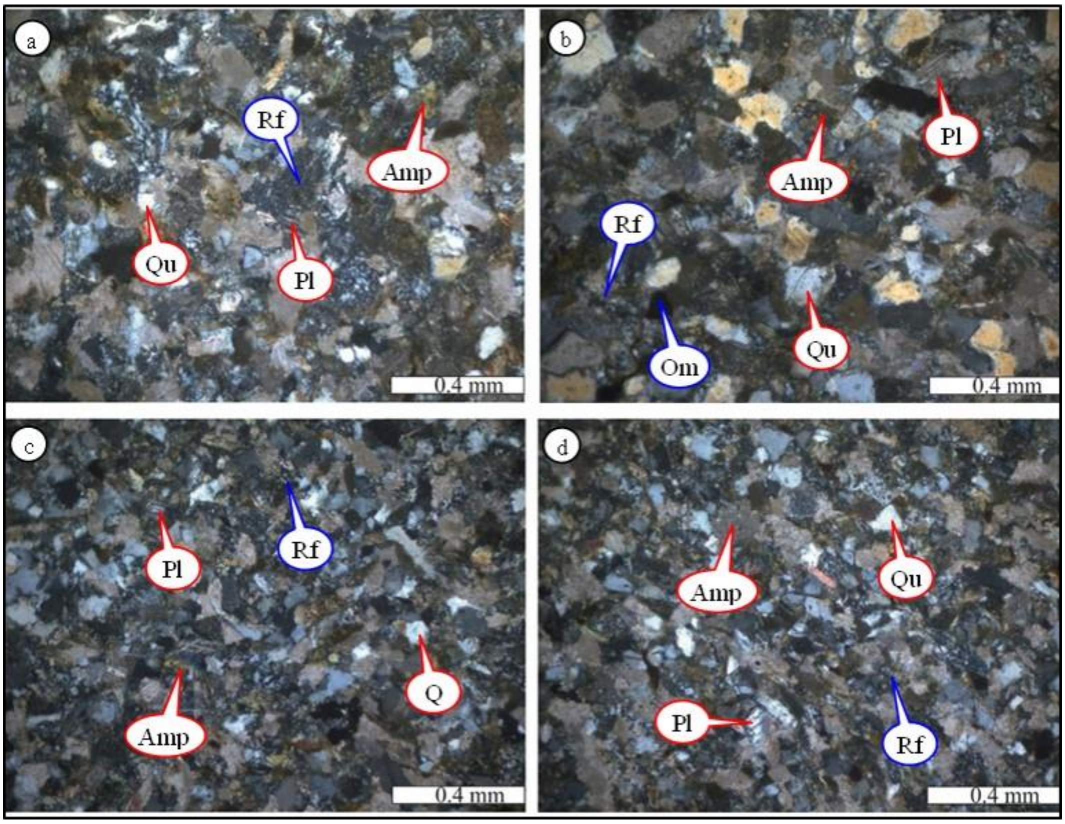

Figure 6. Petrographic images of some sandstone samples on the microscope (XPL) (Pl: Plagioclase, Amp: Amphibole, Qu: Quartz, Om: Opaque mineral, Rf: Rock fragment)

It was determined as a result of experimental studies carried out for determining the physical–mechanical properties of sandstones that the dry unit weight (γ_{dry}) varies between 25.7–26.4 kN/m³, saturated unit weight (γ_{sat}) varies between 25.9–26.5 kN/m³. Total porosity (n) varies between 1.2–2.6% in sandstones used in the study. It was concluded that the water absorption by weight (A_w) varies between 0.4–0.9 % and the water absorption by volume (A_v) varies between 1.1–2.5 % (Table 2). Pycnometer experiment was used for determining the specific gravity (Gs). One set (3 units) of pycnometer test was carried out for each block of sandstones after which their average was calculated. It was determined as a result of the pycnometer tests that the specific gravity value of the sandstones varies between 2.68–2.73 (Table 2).

Table 2. Physical properties of sandstones

	G_s	γ_{dry} (kN/m³)	γ_{sat} (kN/m³)	n (%)	A_v (%)	A_w (%)
Maximum	2.73	26.38	26.51	2.65	2.53	0.95
Minimum	2.68	25.73	25.93	1.18	1.13	0.42
Average	2.71	26.04	26.23	2.25	1.92	0.72
Standard D.	0.01	0.12	0.10	0.36	0.32	0.12

G_s: Specific gravity, γ_{dry}: Dry unit weight, γ_{sat}: Saturated unit weight,
n: Porosity, A_v: Water absorption by volume, A_w: Water absorption by weight

Ultrasonic velocity tests were performed for 5 different saturation conditions on the anisotropic sandstone specimens prepared in accordance with the guidelines suggested by ISRM (2007). A total of 75 specimens were used in order to make ultrasonic wave velocity measurements at different degrees of saturation with 15 specimens for each anisotropy orientation. The average of the P wave velocity (V_p) measured for the sandstones was used while evaluating the test results (Table 3).

Table 3. Average V_p values determined for sandstones according to different anisotropy orientation and degrees of saturation

Saturation degree (S_r, %)	Vp (m/sec) Anisotropy orientation (*β*)				
	0°	**30°**	**45°**	**60°**	**90°**
0	4769	4529	4343	4330	4359
25	4783	4572	4432	4407	4383
50	4897	4629	4536	4501	4459
75	4865	4648	4648	4574	4566
100	5162	4980	4979	4897	4917

Figure 7a shows the graph of the change in the measured P wave velocity values of the specimens with different anisotropy orientations for varying saturation conditions. It was observed upon an examination of Figure 7a that the P wave velocity has increased distinctively in specimens positioned according to the 0° anisotropy orientation and that the values were lower for specimens positioned according to angles of 30, 45, 60 and 90°. P wave velocity values increased with increasing saturation degree for each anisotropy condition. Figure 7b was obtained when the average values under only different saturation conditions were taken into consideration by ignoring the anisotropy state. In this case, a regular increase was observed in P wave velocity parallel to the increase in saturation (Figure 7b). This can be understood from the fact that the regression coefficient value (R^2: 0.96) for the mathematical relationship between saturation and wave velocity values is high.

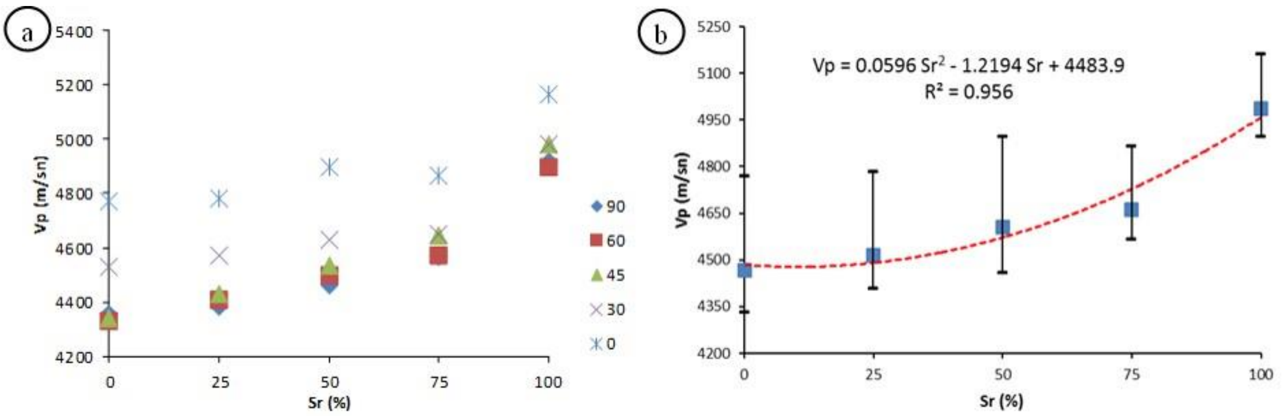

Figure 7. (a) Change in the P wave velocity values of the samples positioned according to different anisotropy degrees and (b) change in V_p values at different saturation conditions without taking into consideration the anisotropy state

UCS (σ_{ci}) of the sandstones was determined by taking into consideration the anisotropy of rock and different saturation degree for the specimens prepared as having a length that is 2.5–3 times greater than the diameter which was then evaluated for each state separately. In addition, Ramamurthy (1993) defined the ratio of the maximum strength ($\sigma_{ci,max}$) value to the minimum ($\sigma_{ci,min}$) strength value as the "anisotropy ratio". This definition as then used as the strength anisotropy ratio (R_{UCS}) in later studies by different researchers (Kumar, 2006; Kim et al., 2016; Kundu et al., 2018).

$$R_{UCS} = \frac{\sigma_{ci,\max}}{\sigma_{ci,\min}} \quad (2)$$

Average UCS values determined for different saturation and anisotropy conditions along with strength anisotropy ratios are given in Table 4

Table 4. Average UCS and strength anisotropy ratio (R_{UCS}) values for different anisotropy orientation and degrees of saturation

Saturation degree (S_r, %)	**Uniaxial compressive strength (σ_{ci}, MPa) Anisotropy orientation (β)**					
	0°	**30°**	**45°**	**60°**	**90°**	**R_{UCS}**
0	162.55	142.20	153.96	163.01	182.15	1.28
25	123.70	95.25	109.66	120.51	136.91	1.44
50	121.06	104.48	106.42	111.69	142.17	1.36
75	109.45	88.56	96.87	101.41	118.85	1.34
100	82.30	61.18	71.48	76.45	91.24	1.49

The change in σ_{ci} values determined using these values and by taking into consideration the anisotropy and different saturation state of rock has been presented as a graph in Figure 8a. In addition, another graph for the change in the average σ_{ci} values under different saturation degree without the inclusion of the change in anisotropy has also been prepared (Figure 8b).

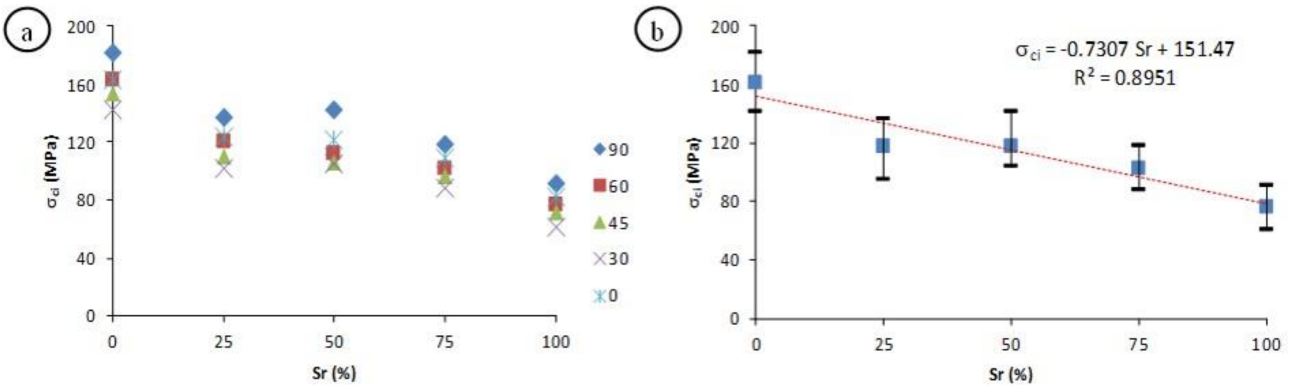

Figure 8. (a) Change in σ_{ci} values measured at changing saturation conditions for the samples positioned according to different anisotropy angles and (b) change in the average σ_{ci} values under different saturation conditions independent of anisotropy situation

When the anisotropy situation was considered, the highest strength values for the sandstone specimens were observed in samples with an anisotropy orientation (β) of 90°. Whereas the lowest strength value was observed in specimens with an anisotropy orientation of 30° (Figure 8a). In addition, it was observed upon an examination of the average values for the uniaxial compressive test results independent of anisotropy that the strength values of sandstone rock specimens decreased at a statistically significant level depending on the increase in the saturation degree (Figure 8b).

Indirect tensile strength values of the samples were determined at different saturation conditions by taking into consideration the changing anisotropy orientations. Average indirect tensile strength values have been reported in Table 5.

Table 5. Average indirect tensile strength values for different anisotropy orientation and degrees of saturation

Saturation degree (S_r, %)	Indirect tensile strength (σ_t, MPa) Anisotropy orientation (β)				
	0°	30°	45°	60°	90°
0	14.38	13.90	13.76	12.67	14.34
25	15.22	13.80	13.79	13.19	15.59
50	14.70	13.31	12.70	10.83	12.99
75	14.06	10.97	9.77	8.48	12.54
100	12.16	8.26	7.84	6.84	10.93

The data included in Table 5 have been evaluated in two ways similar to the previous experiment and measurement results. First of all, the changes in both load direction orientation and saturation degrees were taken into consideration and the change in indirect tensile strength values was examined (Figure 9a). Secondly, a graph was prepared for the indirect tensile strength average values determined only for different saturation degrees without allowing for any anisotropic changes in the specimens (Figure 9b).

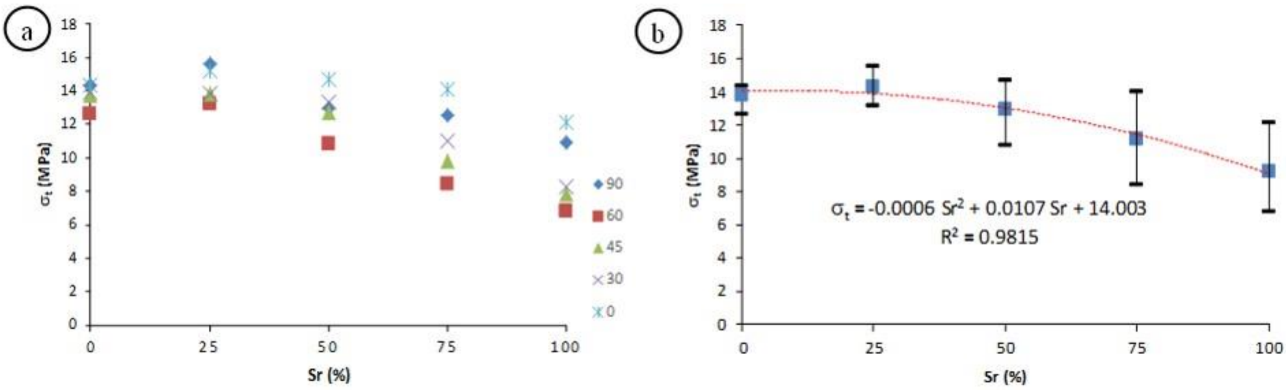

Figure 9. (a) Change in σ_t values for the samples positioned according to different anisotropy orientation measured in changing saturation conditions and (b) change in the average σ_t values in different saturation conditions without considering the situation of anisotropy

It was determined that in general the indirect tensile strength values were lowest for specimens with an anisotropy orientation of 60° with the loading direction. In addition, specimens which were parallel (0°) and perpendicular (90°) to lamination had the highest indirect tensile strength values (Figure 9a). It is observed that tensile strength decreases based on increasing saturation in cases when the situation of anisotropy is not allowed for (Figure 9b).

In the study, using the regression value (R^2), the correlation coefficient (r) was tested both in 95 % level of significance and at n–2 degrees of freedom through the equation 3 by using t-test and compared with the correlation coefficient value (r) and critical r value of Pearson correlation coefficient.

$$t = r\sqrt{\frac{n-2}{1-r^2}} \tag{3}$$

where t: t–test, n; number of sample and r; correlation coefficient.

In the determination of significance with t-test, t value (t_{cal}) that was calculated from equation 3 was compared with the t value that was obtained from standard t tables (t_{tab}) (Alkan and Dağ, 2018). Since the correlation coefficient is significant, it is required that the t value calculated from equation 3 is larger than the value of t table. In the second case, if the relation is significant, correlation coefficient having been determined for variables has to be greater than the Pearson critical r value correlation coefficient value. Within the scope of statistical studies, the evaluations related to the analysis are presented in Table 6.

Table 6. Validation of simple regression analysis

Relations	Sample number	Equation	R^2	r	Pearson critical r	t_{cal}	t_{tab}
V_p-Sr	5	V_p =0.0596Sr^2 – 1.2194 Sr + 4483.9	0.96	0.98	0.878	8.07	2.57
σ_{ci}-Sr	5	σ_{ci} =-0.7307Sr +151.47	0.89	0.95	0.878	5.06	2.57
σ_t-Sr	5	σ_t =-0.0006Sr^2 – 0.0107 Sr + 14.003	0.98	0.99	0.878	12.79	2.57

When Table 6 is examined, it is seen that for the V_p–Sr, σ_{ci} – Sr and σ_t–Sr analysis calculated t value is larger than table t and all determined correlation coefficients were bigger than Pearson critical correlation coefficient value. This means that correlation coefficients were significant.

5. Discussion

Anisotropy and saturation conditions that have an impact on rock behavior were evaluated together within the scope of this study. It can be stated upon a review of relevant literature studies that there are studies which separately examine the effects of anisotropy or saturation degrees on rock behavior. However, no study was observed in the literature which examines the integrated impact of both properties. Only Kumar (2006) and Kundu et al. (2018), have taken into consideration the dry and saturated conditions while carrying out evaluations on rocks which display anisotropic characteristics. Whereas in this study, different saturations other than dry and saturated conditions have also been evaluated as a parameter different than the studies in the literature.

Heidari et al. (2013), carried out studies regarding the petrographic and engineering characteristics of sandstones. The dry unit weight values (γ_{dry}) for the sandstones used in the study varied between 21.5–25.9 kN/m³, whereas the saturated unit weight values (γ_{sat}) varied between 22.3–27.2 kN/m³ and the porosity values (n) varied between 3.4–17.5 %. The dry unit weight values (γ_{dry}) of the Mescitli sandstones used in this study varied between 25.7–26.4 kN/m³, saturated unit weight values varied between (γ_{sat}) 25.9–26.5 kN/m³ and porosity values (n) varied between 1.5–2.5 (Table 2). It can be stated that the sandstones used in this study have a more homogeneous composition, lower porosity and higher strength in comparison with those used in the study by Heidari et al., (2013).

Karakul and Ulusay (2012), examined the changes in P wave velocity of different rock types under different saturation conditions. Two tendencies were observed in P wave velocity as increase and decrease depending on increasing saturation. The decrease in P wave velocity based on the increase in saturation was pointed out to be due to the increase in clay content in the rock. In addition, the researchers have also examined in the same study the relationship under changing saturation conditions between P wave velocity and various strength characteristics such as UCS and indirect tensile strength. It was observed that the strength characteristics increased with increasing P wave velocity. In addition, it was also observed that the strength values decreased from dry to saturate.

Ajalloeian and Lashkaripour (2000), determined that the P wave measurements in shale and silt stones under changing anisotropy situations decreased from 0˚ to 90˚. Chen and Hu (2003), carried out experimental studies on partially weak sandstones with certain amounts of smectite, illite, chlorite and kaolinite content and determined the values for UCS and wave velocity. P wave velocity values of sandstones varied between 480–4840 m/sec. UCS values varied between 0.25–18.98 MPa for different sandstone samples. These values are low in proportion to the values that were determined in literature for the same type of rocks. The increase in clay content, porosity and water content was effective in the low values for strength and wave velocity. Török and Vásárhelyi (2010), examined the relationship between wave velocity and UCS in both saturated and dry conditions. It was put forth that increasing wave velocity values resulted in an increase in strength values and that higher strength values were observed in dry samples. Vásárhelyi (2003), also carried out experimental studies on sandstone specimens in which uniaxial compressive strength, tangent and secant modulus of elasticity values were compared for both dry and saturated conditions. A linear relationship of R^2: 0.91 was determined between dry and saturated UCS values. It was determined that the UCS value decreased with a 20 % dependence on saturation in saturated specimens. It was put forth in this study in accordance with literature that the P wave velocity values increased depending on saturation (Figure 7b). Strength values also increased based on the increase in P wave velocity values for a constant saturation condition. In addition, it was also observed that the UCS values decreased depending on the increase in the saturation degree (Figure 8b).

It has generally been observed in studies in the literature which examine the impact of anisotropy on rock behavior that the highest UCS values are attained at anisotropy orientations of 0° and 90°, while the lowest UCS is observed in anisotropy orientations of 30° (e.g. Ramamurthy, 1993; Ajalloeian and Lashkaripour, 2000; Singh et al., 2015; Kim et al., 2016; Kundu et al., 2018). In summary, previous studies have shown that the orientation of bedding planes has a clear influence on rock strength. However, the type of influence may be different depending on the rock types (Kim et al., 2016). Similarly, highest strength values have also been observed in this study for specimens that are perpendicular and parallel to lamination, while the lowest strength values were observed in samples with an anisotropy orientation of 30° (Table 4, Figure 8a). It was found result this study that, the curve of the strength anisotropy is U-type with a maximum strength is β=0˚ or 90˚ and minimum strength is β=between 20-40˚ as early studies (e.g. Donath, 1964; Ramamurthy, 1993; Matsukara et al., 2002).

It was determined upon an examination of studies in the literature that strength anisotropy in sandstones has been determined as 1.56, 1.49 and 1.40 by Yaşar (2001), Zhang et al. (2010), Kim et al. (2016) respectively. In this study, the strength anisotropy of Mescitli sandstones varied between 1.28–1.49 depending on different saturation conditions (Table 4). The anisotropy ratio values obtained in both the studies in literature and in this study are close and indicate low anisotropy according to Ramamurthy (1993).

6. Conclusions

The literature survey shows that anisotropy and saturation have a significant impact on rock behavior. In this study, the integrated effect of changes in geomechanical properties that may occur under changing saturation conditions for Mescitli (Gümüşhane, NE Turkey) sandstones positioned according to different anisotropy orientations along with degrees of saturation and anisotropy on strength have been examined. The conclusions regarding the study are as follows.

Sandstones are included in the “low anisotropy” category when evaluated according to strength anisotropy. It was observed that the strength values of dry specimens are higher under changing anisotropy conditions and that strength values decreased significantly in saturated specimens. In addition, it was also determined that the specimens that are perpendicular and parallel to lamination have higher strength values in comparison with specimens that have various other anisotropy orientations and that the lowest strength values were determined in specimens with anisotropy orientation of 30°.

It was determined that the indirect tensile strength values of dry specimens under changing anisotropy conditions were higher. It was also observed that the saturated specimens had distinctively lower indirect tensile strength values. In addition, it was also determined when anisotropy conditions were taken into consideration that specimens that are parallel and perpendicular to lamination have higher tensile strength values and that the specimens with 60° anisotropy orientation had low tensile strength values in almost all saturation cases.

Whereas the P wave velocity values are higher for specimens that are parallel to lamination, the lowest P wave velocity values were measured in specimens that are perpendicular to lamination. Similarly, while the P wave velocity values were lower for dry specimens, increases were observed depending on saturation degree.

According to the graphs and equations related to the V_p-Sr, σ_{ci}–Sr and σ_t–Sr analysis correlation coefficients were significant statistically. The relations and equations obtained from the study are valid for Mescitli sandstones.

It was determined based on the results obtained in this study that various physical and mechanical properties of Mescitli sandstones depend on changing saturation and anisotropy conditions. Generalizations should not be made since rock environments are anisotropic, heterogeneous and discontinuous and the results acquired in this study should not be used for rocks with similar lithologies from other regions.

Author contribution

Zarife Gültekin: Field studies, Investigation, Laboratory studies, Writing–original draft.
Serhat Dağ: Supervision, Field studies, Investigation, Laboratory studies, Data analysis, Conceptualization, Writing–original draft.

Declaration of ethical code

The authors of this article declare that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflict of interest

The authors declare that they have no conflict of interest.

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