Acta Geodyn. Geomater., Vol. 23, No. 2 (222), 223–234, 2026
DOI: 10.13168/AGG.2026.0014

journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

EVALUATION OF ANISOTROPY IN ROCKS USING NON-DESTRUCTIVE TESTING METHODS

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ARTICLE INFO

Article history:
Received 26 November 2025
Accepted 23 March 2026
Available online 31 March 2026

Keywords:
Anisotropy
Leeb hardness
Schmidt hammer rebound
P-wave velocity
Non-destructive testing

ABSTRACT

In engineering projects and rock mechanics studies, it is important to determine the physical strength properties of rocks. In these studies, the anisotropy property, which represents the expression of the change in the properties of the rocks according to the directions, is one of the main parameters that directly affects the preparation of project planning. A non-destructive, fast, and economical determination of this parameter in situ can be very useful. In this study, the anisotropic features of different types of rocks (sedimentary, magmatic and metamorphic) were researched using the non-destructive tests (NDT), commonly used in recent years, of surface hardness (Schmidt hammer rebound values and Leeb hardness) and P-wave velocity (Vp). According to the findings obtained, limitations of the surface hardness test devices (small device probe area) were determined to cause deviations in the measurement values. As P-wave measurements were less affected by the surface features of the samples and provided more reliable information about the structural-textural features of the samples, they have better useability for determining the anisotropic features of rocks.

1. INTRODUCTION

Changes in the textural (grain orientation and alignment of micro cracks), physical (density, porosity, permeability, P-wave velocity, and capillary water absorption value), and strength (uniaxial compressive strength and point load strength), hardness (Shore hardness, Schmidt hammer rebound value, Leeb hardness, etc.) properties of the rocks due to directions are defined as anisotropy. Anisotropy in rocks can develop under the influence of the formation processes of the rocks or the temperature and pressure to which they are subsequently exposed. In sedimentary rocks, the difference in the texture and structural properties of the rock according to the directions after the sedimentation and diagenesis processes causes significant anisotropy in the rock mechanics properties. Anisotropy in igneous rocks is caused by different factors such as aligned grain fabric, preferred crystal orientation, the geometry of the void space, or the alignment of microcracks in preferred directions (Forestieri et al., 2017). In metamorphic rocks, the rocks acquire anisotropic properties due to the alignment of microcracks and the elongation of the grains in the preferred directions depending on the temperature and active pressure in the formation process. Anisotropy is a significant parameter to consider in rock mechanics and engineering applications (Cho et al., 2012; Yun et al., 2013). The relationship between the anisotropy properties of rocks and physical (Apuani et al., 1997; García-del-Cura et al., 2012; Çobanoğlu, 2020; Kolay et al., 2022), strength (Forestieri et al., 2017; Douglass and Voight, 1969; Takemura et al., 2003; Güney et al., 2004; Nasseri and Mohanty, 2008), wear resistance (Gökçe, 2015; Özvan and İnan, 2020), shear energy (Ersoy and Atıcı, 2005; Ozcelik and Yilmazkaya, 2011), deterioration (Fort et al., 2008), and textural (Forestieri et al., 2017; Douglass and Voight, 1969; Takemura et al., 2003; Nasseri and Mohanty, 2008) properties has been studied by many researchers.

Apuani et al. (1997) investigated the relationship between the variation of wave velocity and tensile strength for directions in orthogneiss. They found significant correlations between P-wave velocities and tensile strength for gneiss in the plane perpendicular to the schistosity and in the direction of maximum elongation of crystals. Güney et al. (2004) investigated the change in Shore hardness according to the directions in 9 different marble samples and declared that Shore hardness changes according to the directions. To be able to determine the Shore hardness value of rocks more reliably, the Shore hardness values were measured in the x, y and z directions of the cube samples and they stated that the arithmetic mean of these measurements should be noted. Ozcelik and Yilmazkaya (2011) stated in their study that the cutting efficiency of diamond wire cutting is sensitive to rock anisotropy and that cutting operations are cost-

Table 1 Location and lithology of the samples used in the study.

Sample No.	Location	Rock type	Rock name
1	Ereğli/Konya	Sedimentary	Travertine
2	Kızılören/Konya	Sedimentary	Travertine
3	Kâzımkarabekir/Karaman	Sedimentary	Limestone
4	Bağrıkurt/Konya	Metamorphic	Metaconglomerate
5	Marmaraadası/Balıkesir	Metamorphic	Marble
6	Ahlat/Bitlis	Pyroclastic	Lithic tuff
7	Sincan/Ankara	Volcanic	Andesite
8	Yunt/Manisa	Volcanic	Andesite

optimal when performed parallel to the stratification planes. In this study, correlation values between the yield parameters of the diamond wire cutting method (unit wear, cutting rate and specific energy) and cutting angles were identified to be between 0.89 to 0.96. García-del-Cura et al. (2012) classified travertines into 4 types (massive, banded, laminated, and crypto-laminated) according to layer thickness. They stated that the strength properties of banded travertines show significant differences according to directions. They determined the highest strength was perpendicular to low porosity and layering, while the lowest strength values were parallel to high porosity and layering. They also reported that the capillarity values of travertines increase in the direction of lamination. Gökçe (2015) presented that the Böhme abrasion loss of travertines varies according to the cutting direction of the rock (perpendicular and parallel). For surfaces cut perpendicular in travertine samples, the Böhme abrasion loss values were lower, while these values were higher for surfaces cut parallel. Özvan and İnan (2020) also mentioned that the wide disc abrasion test is not suitable for use in rocks showing anisotropy. Çobanoğlu (2020) also investigated the change in the strength value of travertines according to the cutting direction (vein-cut and cross-cut). In this study, it was determined that the strength value of vein-cut samples was 1.45 times higher than cross-cut samples. Kolay et al. (2022) stated that cutting direction is an important factor that directly affects physical and strength parameters in Sarıhıdır travertine. Samples cut parallel to layers were determined to provide more appropriate results for use about the physical and mechanical features.

Some researchers have investigated the relationship between the microstructure of rocks and anisotropy (Forestieri et al., 2017; Douglass and Voight, 1969; Takemura et al., 2003; Nasseri and Mohanty, 2008). Fort et al. (2008) determined that there was no relationship between deterioration and anisotropy after the salt crystallization test on dolostone. Forestieri et al. (2017) stated that the microstructure of the rock (microcrack systems and orientations) affects the physical and mechanical behavior. In addition, the anisotropy of rocks has recently been investigated using image analysis methods (X-ray, three-dimensional X-ray computed tomography, and neutron tomography) (Yun et al., 2013; Gong et al., 2020; Zel et al., 2021; Saur, 2022).

The selection of a rock property that can accurately explain its anisotropy property is increasingly in demand. Practical and inexpensive non-destructive testing techniques (NDTs), which can be used both in situ and in the laboratory, can be used for the detection of anisotropy. For this purpose, samples from different rock groups (sedimentary, magmatic, and metamorphic) were compiled in this presented study. The required number of cube specimens was prepared for each sample. Anisotropy properties of the rocks were investigated by using Schmidt hammer rebound value, Leeb hardness, and P wave velocity on the x, y, and z directions of the cube specimens.

2. MATERIAL AND METHODS

For this study, eight rock samples (travertine, limestone, meta conglomerate, marble, volcanic, and pyroclastic) were collected from quarries operated in different locations in Anatolia. The location and rock types of the samples used in the study are shown in Table 1. Homogeneous rock blocks with dimensions of 20 × 30 × 30 cm were compiled from the operated quarries for experimental studies and cubic samples of 7 × 7 × 7 cm in size were prepared from these blocks for experimental study. To determine the physical (porosity and dry density) properties of the samples, test samples were prepared according to the relevant standards, and the respective tests were carried out according to the standard (TS EN-1936, 2010). To determine the anisotropy property of the prepared samples using non-destructive tests, P-wave velocity and different types of surface hardness (SHR and HL) properties were determined in the x, y, and z directions. The sample surfaces were polished to minimize the effects of surface roughness for the measurements of these tests.

The P-wave velocity test was performed three times following the method recommended in ASTM E494 (2020) and the average values were determined as P-wave velocity. The Schmidt hammer rebound test of the samples was performed following the standard recommended by ASTM D5873 (2014). For this test, an L-type hammer with an impact energy of 0.735 Nm and a plunger diameter of 15 mm was used. To avoid

Fig. 1 Polarizing microscope used for photographing and examining thin sections of samples.

orientation corrections, the hammer was applied at a right angle to the rock block surface. To determine the SHR value, 10 measurements were made on each rock sample and the average was taken. Thereafter, the SHR value of the samples was calculated by subtracting the slingshot recoil numbers of more than seven units from the average and re-averaging the values of the remaining ones. The Leeb hardness test for rock materials does not have a universal standard. Numerous studies have been conducted to develop a standard for this test in rocks (Asiri et al., 2016; Asiri, 2017; Corkum, 2018; Çelik et al., 2020; İnce and Bozdağ, 2021; Çelik et al., 2023; Ghadernejad and Esmaeili, 2024; Ulusay et al., 2025). In these studies, the effect of size on Leeb hardness was investigated on cube and core samples. For cube specimens, an optimum edge length of 7 cm was recommended so that the test results are not affected by the size of the specimens (İnce and Bozdağ, 2021). This test was performed on cube samples with an edge length of 7 cm as recommended by İnce and Bozdağ (2021). The D-probe of the Insize ISH-PHB brand device, which has a spherical impact body made of tungsten carbide cobalt, with an impact energy of 11 Nmm, a diameter of 3.00 mm, and a weight of 5.45 g, was used. Measurements were applied perpendicular to the sample surface. First, the device was calibrated. Then, measurements were made at 20 different impact points evenly distributed over the surface of the sample. The arithmetic mean of the measured values was determined as the HL value for the sample. To determine the petrographic properties of the rocks used in this study, thin sections were prepared considering the method proposed in TS EN-12407 (2019), the samples were examined under a polarizing microscope, and the necessary definitions were made. The changes in the micro textures of the rocks according to the directions were photographed using the Nikon Eclipse E400 pol brand belonging to the Geological Engineering Department of Niğde University (Fig. 1).

3. RESULTS

3.1. MACROSCOPIC AND MICROSCOPIC PROPERTIES OF STONES

Macro and micro views of the samples used in this study are given in Figures 2 and 3. Sample 1 is laminated travertine with dark and light laminations in thin section images of x and y directions (Figs. 2 and 3). Sample 2 is a very porous laminated travertine (Figs. 2 and 3). Sample No. 3 is a limestone showing stromatolitic features in places (Figs. 2 and 3).

Sample No. 4 is a metaconglomerate and the pebbles forming the rock are elongated along the x and y axis (Fig. 2). When the thin section image of this sample was examined, it was determined that the matrix also extended along the x and y axis (Fig. 3). Sample No. 5 is a granoblastic textured marble. When the thin section image of the sample is examined, partial orientation of calcite minerals is observed (Fig. 3).

Sample No. 6 is a tuff rich in lithic material. Fiamme structure is evident in the samples. Samples 7 and 8 are andesite. In the sedimentary rock samples (Samples No. 1, 2, and 3), anisotropy was associated with layer and lamination. In the case of the metaconglomerate rock sample, anisotropy was explained by the different size changes of the gravel grains according to the directions. In the marble sample, it has been observed that banded structures that develop depending on the composition cause anisotropy. The anisotropy in the volcanic rocks was related to a vaguely banded structure depending on their composition. In the last type of rock group, the pyroclastic rocks, the anisotropy was due to the developing fiamme structure associated with the flattened and elongated glassy material.

3.2. SOME PHYSICAL PROPERTIES OF STONES

The physical properties (dry density and porosity) of the rocks used in the study are given in Table 2. While the dry density values of the rocks used in the study ranged from 1.81 to 2.85 g/cm^3, the

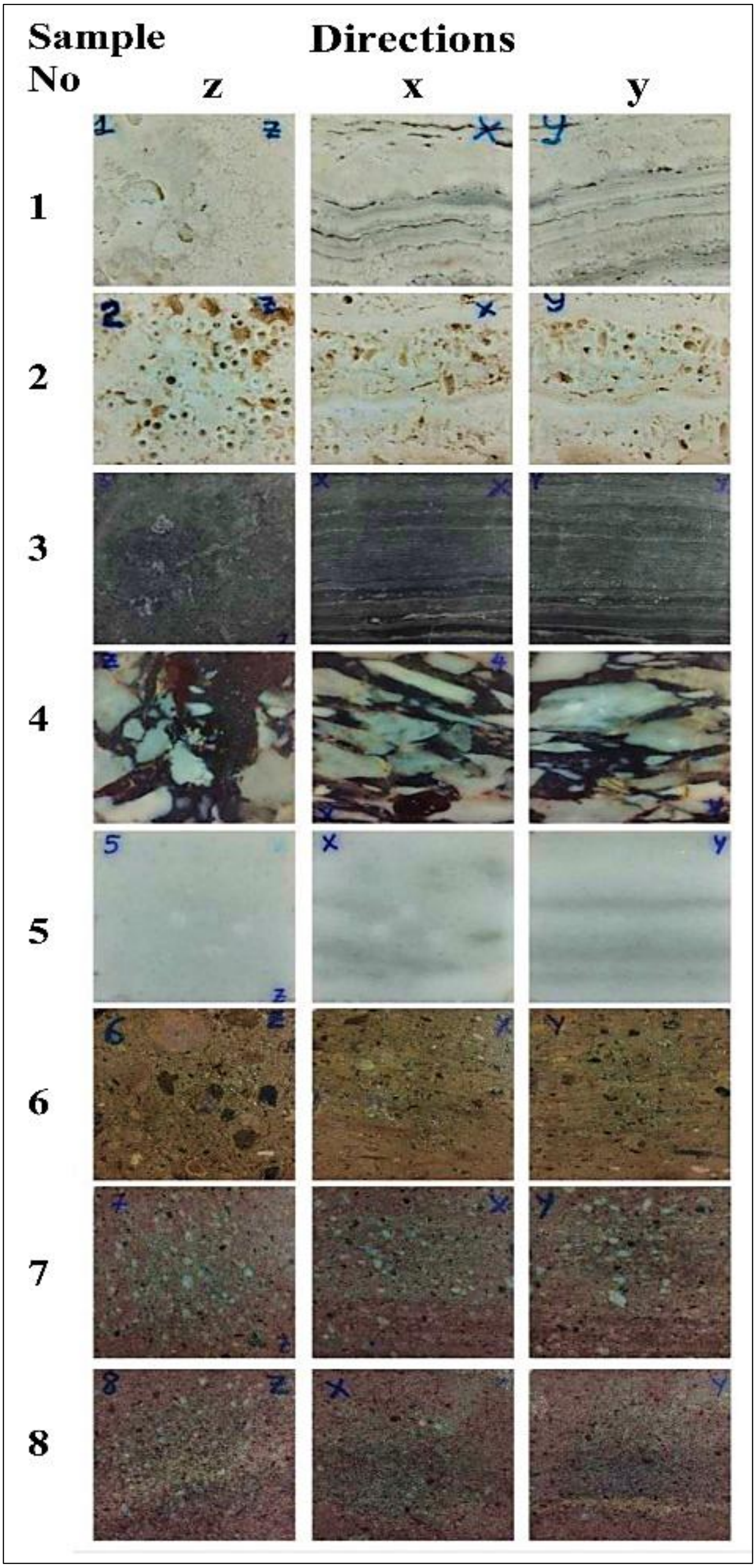

Fig. 2 Macroscopic view of samples according to directions.

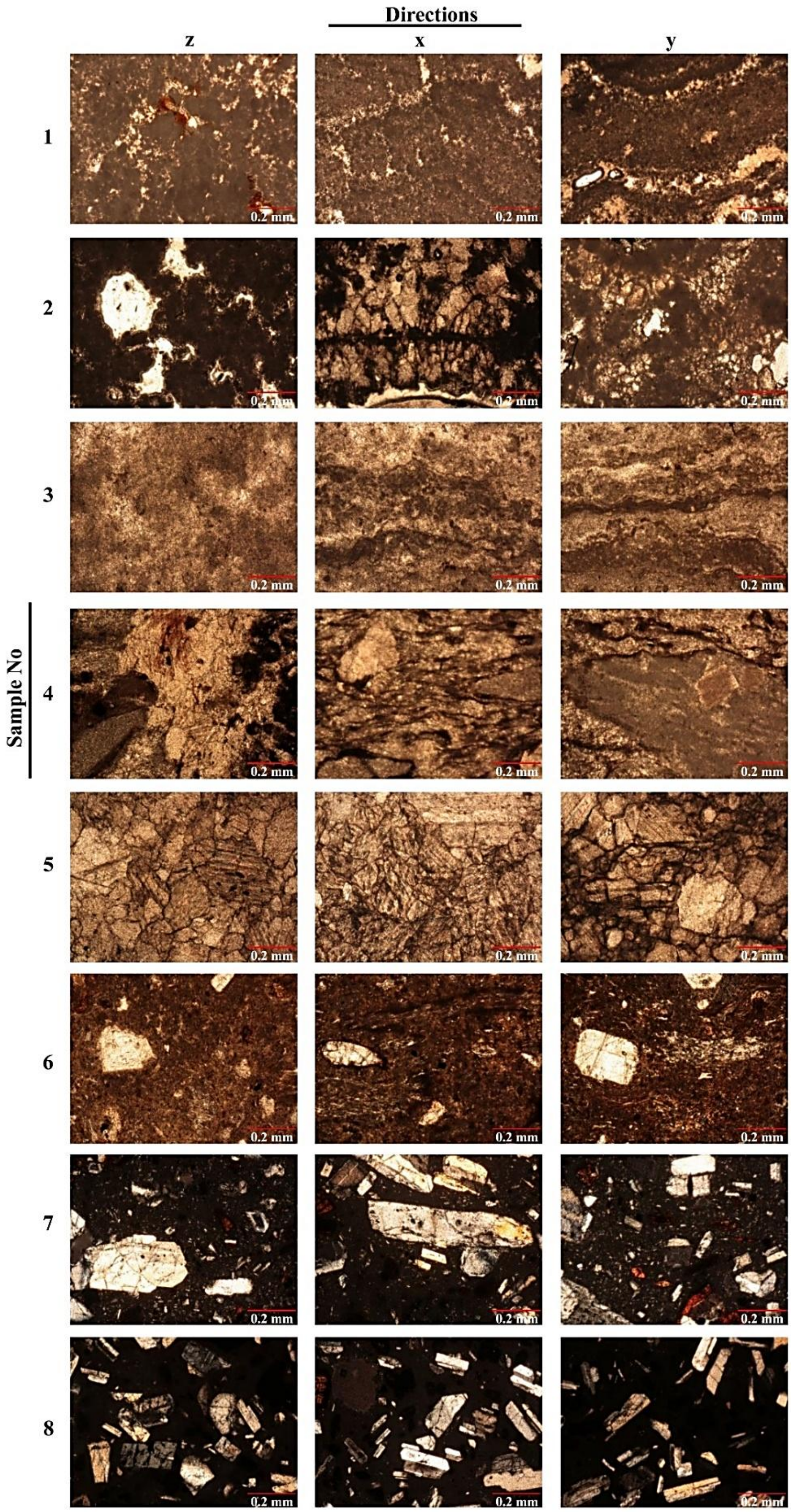

Fig. 3 Microscopic view of samples according to directions (Images for samples No. 1-6 are in plane-polarized light, samples No. 7-8 are in crossed polar).

Table 2 Physical properties of rocks used in the study (n: porosity, ρ_d: dry density).

Sample No.	n-%			ρ_d – g/cm^3		
	Min.	Max.	Mean±Std	Min.	Max.	Mean±Std
1	6.50	7.50	6.97±0.53	2.29	2.37	2.31±0.05
2	7.20	8.10	7.57±0.78	2.13	2.24	2.16±0.06
3	0.65	0.74	0.70±0.04	2.84	2.88	2.85±0.02
4	0.62	0.73	0.68±0.06	2.71	2.74	2.72±0.02
5	0.64	0.70	0.66±0.02	2.67	2.72	2.70±0.03
6	29.10	31.20	29.93±0.87	1.78	1.84	1.81±0.04
7	9.88	10.50	10.06±0.42	2.36	2.41	2.38±0.03
8	6.90	7.22	7.07±0.24	2.28	2.31	2.29±0.02

Table 3 Physical properties of rocks used in the study.

Sample No.	Vp- km/s			HL			SHR		
	x	y	z	x	y	z	x	y	z
1	4.554±0.01	4.497±0.02	3.896±0.02	336.33±25.31	358.00±30.49	366.67±28.64	17.67±2.30	22.67±2.20	12.00±1.30
2	2.527±0.02	2.493±0.02	1.867±0.04	537.33±20.62	504.33±24.46	329.67±19.74	20.00±1.89	20.67±1.75	18.00±1.97
3	6.383±0.02	6.266±0.01	6.479±0.02	770.00±6.74	761.00±8.12	752.00±5.48	53.33±2.55	47.33±2.30	52.00±2.19
4	5.258±0.01	5.150±0.03	4.074±0.02	675.67±35.86	613.00±29.42	622.33±31.37	38.00±3.05	31.33±2.90	36.00±3.15
5	4.172±0.01	3.511±0.01	3.359±0.01	604.00±5.24	571.33±4.87	579.00±8.64	25.33±2.01	26.67±1.84	28.67±1.95
6	2.723±0.02	2.633±0.01	1.886±0.02	368.33±7.45	338.00±8.37	431.67±10.29	14.67±1.25	14.00±1.10	16.33±0.97
7	3.978±0.02	3.980±0.01	3.619±0.01	712.33±8.24	742.33±6.87	691.00±7.68	34.67±2.24	30.00±2.13	34.00±1.90
8	4.249±0.01	4.320±0.01	3.817±0.01	745.87±7.36	685.67±8.74	730.00±8.61	34.33±1.75	34.00±1.89	36.00±1.61

(Vp: P-wave velocity, HL: Leeb hardness, SHR: Schmidt hammer rebound) (mean value±Std. Deviation)

porosity values ranged from 0.66 % to 29.93 %. According to the NBG (1985) dry density classification, samples 1, 2, 6, 7 and 8 were 'very low' density rocks, samples 4 and 5 were 'medium' density rocks and sample 3 represented 'high' density rocks. According to the NBG (1985) porosity classification, the rocks used in the tests showed 'low' (Samples No.: 3, 4 and 5), 'high' (Samples No.: 1, 2, 7, and 8), and 'very high' (Sample No. 6) porous rock properties.

3.3. *CHANGE IN NON-DESTRUCTIVE PROPERTIES OF ROCKS ACCORDING TO DIRECTIONS*

High energy (SHR) and low energy (HL) surface hardness tests and P-wave velocity (Vp) were used to determine the anisotropy property of each rock used in the study. The NDT measurements of the samples by directions (x, y, and z) are given in Table 3.

The variations of HL measurements by directions are given in Figure 4. HL measurements yielded values that were close to each other in some directions in samples No. 3, 4, and 5. The main reason for this result is that the low energy applied by the Leeb hardness device during the measurement is effective only at a shallow depth, and the hardness is controlled by the surface properties. This is directly affected by porosity, mineral diversity (mono- and poly-mineral), and textural properties on the measurement surface. In general, Leeb hardness decreases with increasing porosity of rocks (İnce and Bozdağ, 2021; Çelik and Çobanoğlu, 2023). In addition, the small diameter of the probe used in Leeb hardness measurements causes the samples to be negatively affected by porosity on the application surface (Çelik and Çobanoğlu, 2023). If the rock consists of monomineral, the hardness measurements to be obtained show less variation, while the Leeb hardness measurement values vary in a wide range in building stones containing polyminerals (Çelik and Çobanoğlu, 2023). The components of the pyroclastic rock (pumice, volcanic glass and rock fragments) have been reported to affect the Leeb hardness to a large extent (Balcı and İnce, 2024; İnce et al., 2025a). Some researchers have reported a high correlation between the microstructural properties (grain compactness, aspect ratio, shape factor, grain size homogeneity, and texture coefficient) of rocks (sedimentary and igneous) and Leeb hardness (İnce and Bozdağ, 2021; Ghorbani, 2022). In addition, the small tip area of the probe of this device causes it to be affected by the pores on the surface. The pores on the surface of travertine samples 1 and 2 directly affected the HL value (Fig. 2). Travertine samples No. 1 and 2 have high standard deviation values. (Table 3). These deviations are explained by the fact that the porosity of the rock directly affects the HL value, as emphasized by previous researchers (Ghorbani, 2022; Çelik and Çobanoğlu, 2023). In limestone sample number 3, when the HL test is applied perpendicular to the anisotropic planes (lamination), HL values obtained were close to each other in the x and y directions related to the absorption of impact energy by these planes. The different hardness and size of the minerals and/or grains on the surface is another factor that directly affects the HL value (İnce and Bozdağ, 2021;

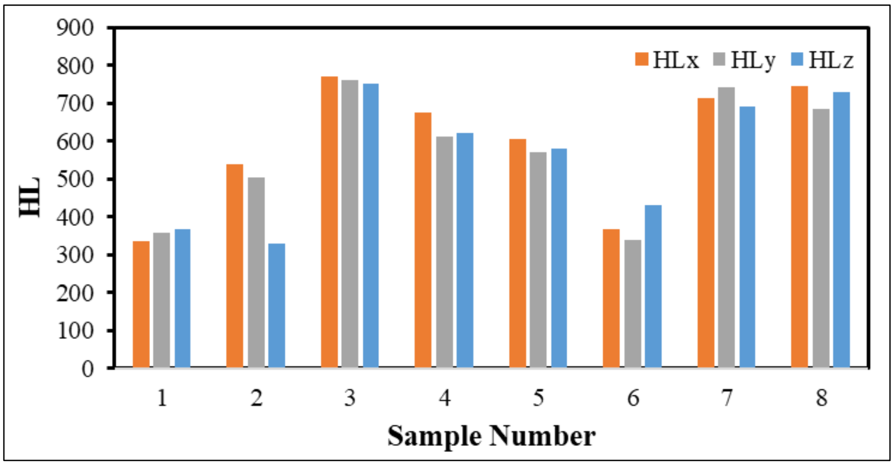

Fig. 4 Change in the HL values of the samples by directions.

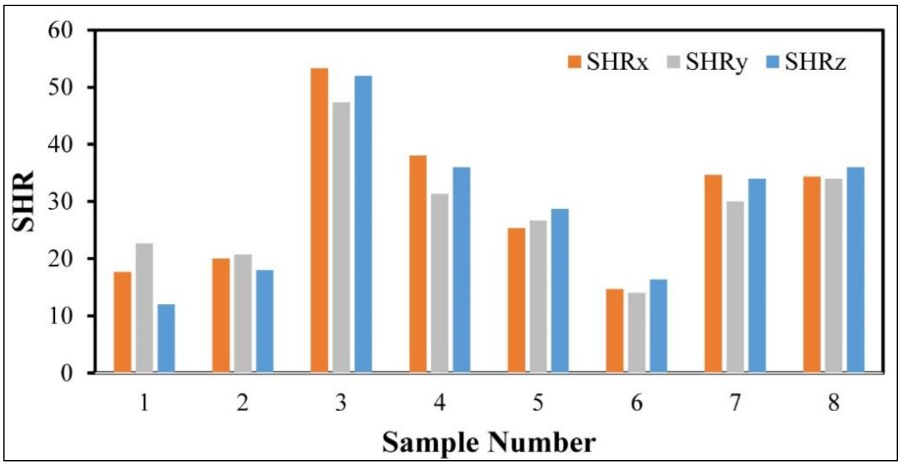

Fig. 5 Change in the SHR values of the samples by directions.

Balcı and İnce, 2024; İnce et al., 2025a). This situation is seen in metaconglomerate sample number 4. It was determined that the difference in coarse grain size and hardness values between grain and matrix directly affected the HL value of this sample (Fig. 2). In sample No. 4, the HL value of the z surface was determined 622.33. For this sample, the average of the measurements of the HL value of the pebble grains in the Z direction is 650, while the average of the HL values obtained from the matrix is 608. All surface measurements of the other samples were measured differently from each other. In marble sample number 5, in spite of the rock comprising a single mineral, different HL values were obtained based on the orientation of the sample. This situation may be explained by the differences in mineral dimensions comprising the rock. HL values were determined to be different in all directions (x, y and z) in samples of volcanic rock like andesite (samples 7 and 8) and lithic tuff (sample 6).

Graphs of the SHR measurements of the samples are given in Figure 5. The SHR values in the x, y, and z directions of all samples were determined differently. However, pores on the measuring surface and/or mineral/grain sizes affected the SHR measurement (Aydin and Basu, 2005; Aydin, 2014; Ajalloeian et al., 2020; Kong et al., 2021). Kong et al. (2021) emphasized that SHR values should be used very carefully, especially if the mineral or grain size forming the rock is larger than the hammer piston tip diameter. In sample No. 4, large deviations in the SHR value were detected due to the coarse gravel. In addition, the SHR values of the matrix and the coarse-grained limestone gravels in sample No. 4 differed from each other. These differences caused the standard deviation values of the SHR value of this sample to increase. Özbek (2009) stated that SHR values can vary up to 25 % according to grain and matrix distribution. In addition, in the regions where small diameter pores are concentrated in travertine samples No. 1 and 2, decreases in the SHR values of the rocks were determined. For volcanic rocks with similar mineralogical composition (samples 7 and 8), the SHR values were between 30.00 and 36.00. There are also studies indicating that the SHR test is affected by the size factor (Demirdag et al., 2009; Aydin, 2014). In these studies, the optimum sample edge lengths for cube samples vary. Although the sample size in this study is constant in itself, it is thought that it may pose disadvantages when compared to other studies.

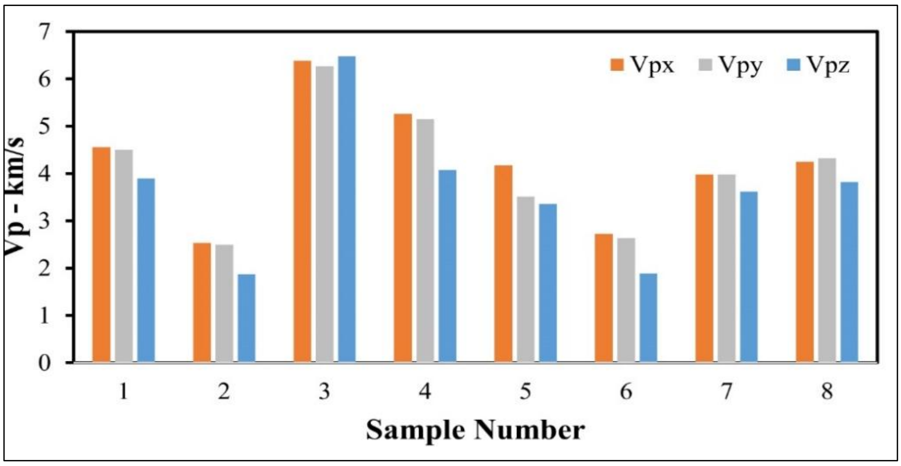

Fig. 6 Change in the Vp values of the samples by directions.

Table 4 NDT (Vp, HL, and SHR) values of the rocks according to directions.

Sample No.	Vp- km/s			HL			SHR		
	z/z	x/z	y/z	z/z	x/z	y/z	z/z	x/z	y/z
1	1.00	1.17	1.15	1.00	0.92	0.98	1.00	1.47	1.89
2	1.00	1.35	1.34	1.00	1.63	1.53	1.00	1.11	1.15
3	1.00	0.99	0.97	1.00	1.02	1.01	1.00	1.03	0.91
4	1.00	1.29	1.26	1.00	1.09	0.99	1.00	1.06	0.87
5	1.00	1.24	1.05	1.00	1.04	0.99	1.00	0.88	0.93
6	1.00	1.44	1.40	1.00	0.85	0.78	1.00	0.90	0.86
7	1.00	1.10	1.10	1.00	1.03	1.07	1.00	1.02	0.88
8	1.00	1.11	1.13	1.00	1.02	0.94	1.00	0.95	0.94

There are many factors (rock type, density, shape and grain size, porosity, anisotropy, environmental pressure, pore water, temperature, etc.) that affect the P-wave velocity of rocks (Fener, 2011). Among these factors, microcracks, porosity, shape, grain size, and grain orientation are the prominent parameters in the variation of P-wave velocity according to the directions of the rock (Vajdová et al., 1999; Kern et al., 2008; Zerrouki et al., 2022). The graphs of the Vp measurements of the samples used in the study are given in Figure 6. When Figure 6 was examined, the Vp values of samples No. 7 and 8 (volcanic rocks) measured in the x and y directions were close to each other. Travertine samples number 1 and 2 had partly similar values for Vp measured in the x and y directions, while values measured in the z direction were very different. For the metaconglomerate sample number 4, the Vp values were observed to be very different in all directions linked to the orientation of the clasts (Vpx: 5.258 km/s, Vpy: 5.150 km/s, Vpz: 4.074 km/s). In the other samples, the Vp values were different according to direction. When macro and micro images are evaluated together, it can be seen that the most effective factor in the variation of Vp value according to directions is the orientation of minerals or grains (Fig. 3).

The changes of NDT values of the samples according to the directions are shown in Figures 4-6, it is seen that SHR, HL and Vp values are incompatible within itself. This situation can be explained by the differences in rock properties (porosity, mineral diversity and textural properties) that directly affect the surface hardness methods and the differences in the test probe application surface area (SHR probe diameter 15 mm, HL probe diameter 3 mm).

The proportional changes of the NDT (SHR, HL, and Vp) measurements made in the x, y, and z directions of the studied samples according to the z-axis are given in Table 4. The fact that the obtained values moved away from 1.00 shows that the samples are anisotropic. When Table 4 was examined, it was found that although the x/z and y/z ratios of the NDT (Vp, HL, and SHR) values of sample 3 were very close to 1, they appeared to be anisotropic in the macro images of the samples.

In sample 5, although the ratio of HL measurements in the x and y directions to the measurement in the z direction was close, the anisotropy observed in the macro images could not be determined. When the thin section images of sample No. 5 were examined, it was determined that calcite minerals were partially oriented in the x and y directions (Fig. 3). Considering these data, the results from the approach indicated that they are not safe for anisotropy assessment.

The equations proposed by some researchers to calculate the anisotropy coefficient of rocks relative to the P-wave velocity (Eqs. 1 and 2) were revised according to other NDT properties (Eqs. 3-6).

Table 5 Anisotropy coefficient values of the samples.

Sample No.	Vp		SHR		HL	
	k*	k**	k***	k****	k*****	k******
1	15.26	14.46	61.146	47.06	8.58	8.27
2	28.74	26.11	13.636	12.90	45.43	38.65
3	3.34	3.29	11.790	11.25	2.37	2.34
4	24.53	22.52	18.987	17.54	9.84	9.27
5	22.09	19.49	12.397	11.63	5.59	5.41
6	34.68	30.74	15.556	14.29	24.69	21.70
7	9.36	9.07	14.189	13.46	7.18	6.92
8	12.16	11.63	5.751	5.56	8.33	8.05

* Eq. (1), ** Eq. (2), *** Eq. (3), **** Eq. (4), ***** Eq. (5), and ****** Eq. (6)

The anisotropy coefficient suggested by Birch (1988) according to Vp values is given in Eq. (1).

$$k = \frac{V_{pmax} - V_{pmin}}{V_{pmean}} 100 \tag{1}$$

where V_{pmax} is the largest Vp, V_{pmin} is the smallest Vp value, and V_{pmean} is the average Vp value. The ‚nisotropy coefficient proposed by Ruedrich and Siegesmund (2007) can be calculated using Eq. (2).

$$k = \frac{V_{pmax} - V_{pmin}}{V_{pmax}} 100 \tag{2}$$

where V_{pmax} is the largest Vp, and V_{pmin} is the smallest Vp value.

$$k = \frac{SHR_{max} - SHR_{min}}{SHR_{mean}} 100 \tag{3}$$

$$k = \frac{SHR_{max} - SHR_{min}}{SHR_{max}} 100 \tag{4}$$

where k is the coefficient of anisotropy, SHR_{max} is the largest SHR value, SHR_{min} is the smallest SHR value, and SHR_{mean} is the average SHR value.

$$k = \frac{LH_{max} - LH_{min}}{LH_{mean}} 100 \tag{5}$$

$$k = \frac{LH_{max} - LH_{min}}{LH_{max}} 100 \tag{6}$$

where k is the coefficient of anisotropy, HL_{max} is the largest HL value, HL_{min} is the smallest HL value, and HL_{mean} is the average HL value.

The anisotropy coefficient values obtained from Eqs. 1-6 are given in Table 5. When Table 5 was examined, the anisotropy coefficient of all the study samples was greater than 1.00 according to the NDT measurements. Considering these results, all the samples showed anisotropic properties.

Previous investigations have shown that differences in the direction of placement of building stone blocks used in monuments accelerate atmospheric deterioration processes (Fener and İnce, 2015; Gökçe et al., 2016). This is a direct consequence of anisotropy in rocks that cannot be observed at the macro scale. Anisotropy, which cannot be observed at the macro scale in rocks, can be determined using non-destructive testing (NDT) methods. The use of these methods can contribute to a more accurate understanding of the deterioration processes of building stones in monuments and contribute to restoration work, thereby increasing the service life of monuments.

4. DISCUSSION

In recent years, the prediction of the physical and strength parameters of rocks using NDT methods (SHR, HL, P-wave velocity, etc.) and synthesis of preliminary data about construction stones in cultural heritage sites has become more popular (Çelik and Çobanoğlu, 2019; İnce et al., 2025a-b; Ulusay et al., 2025; Karakaya and İnce, 2025). In this study, the anisotropic features of rocks were researched using surface hardness devices working with both high-energy (SHR) and low-energy (HL) impact mechanisms. The purpose was to see the effects of the differences in energy (SHR: 0.735 Nm, HL: 11 Nmm) and the area of the probe (SHR: 15 mm, HL: 3 mm) when determining anisotropy with commonly-used surface hardness devices. As emphasized by previous researchers, these two surface hardness devices are directly affected by the surface features of the rock (Ajalloeian et al., 2020; Kong et al., 2021; İnce and Bozdağ, 2021; Çelik and Çobanoğlu, 2023; Balcı and İnce, 2024; İnce et al., 2025a). In this study, the low-energy and small application area HL test was directly affected by compositional differences and pores on the rock surface. This situation is consistent with the findings of previous (Çelik and Çobanoğlu, 2023; Balcı and İnce, 2024; İnce et al., 2025a) researchers. When the results of the SHR test with high impact energy are investigated, they were affected by the rock surface composition. As emphasized by some researchers, the values obtained with the SHR test may display significant variations linked to the sample size and impact direction of the probe, and these elements should not be ignored (Demirdag et al., 2009; Aydın, 2009; 2014). As stated by Aydın (2009), in situations where the Schmidt hammer probe is applied perpendicular to the anisotropic planes of the rock, clear reductions will occur in SHR values due to absorption of the energy by these planes. Additionally, several studies in the literature revealed the need to definitely consider the effect of sample size when interpreting the SHR test results (Demirdag et al., 2009; Aydın, 2009; 2014). Though the two surface hardness tests used in this study (SHR and HL) obtained more successful results when determining the anisotropic features of samples comprising grains or minerals with equal sizes, when assessed in general, the correlation between surface hardness and rock anisotropy was not very pronounced. For this observation, it will be beneficial to investigate by researching more rock samples. P-wave velocity is one of the most important methods to investigate the petrophysical and strength features of rocks (Benavente et al., 2009; Vasconcelos et al., 2008). Researchers emphasized that P-wave velocity is a good method in the presence of anisotropy and to determine general orientation (Apuanı et al., 1997; Fort et al., 2011). In this study, P-wave velocity was identified to be the best method to determine anisotropy features in different rock groups.

5. CONCLUSIONS

The following results were obtained from tests conducted to evaluate the use of NDTs in determining the anisotropic properties of rocks:

- Equations were developed to determine whether rocks have anisotropic properties according to Vp, SHR, and HL values.
- As some microstructures developing in rocks (fiamme, banded structures, lamination, etc.) cause anisotropy, macroscopic observations are generally inadequate to determine anisotropic features of rocks. It is recommended to supplement macroscopic observations with microscopic examinations.
- In the SHR and HL tests, the limited application surface area, the pores on the rock surface, and the differences in mineral/grain sizes directly affected the measurement values. These features cause high standard deviation values for the mean HL and SHR values of rocks.
- For rocks with similar composition (travertine, volcanic rocks), the SHR values were determined to vary in a very narrow interval (for travertine: 12.00-22.67; for andesite: 30.00-36.00). This situation makes it challenging to determine anisotropy effects with the SHR test, which has a narrow measurement interval (10-100).
- The Vp values measured in the x and y directions on samples number 7 and 8 were very similar, while the Vp values of other samples were determined to differ according to orientation. Since the P-wave velocity values are directly related to both the outer surface and internal structure of the rock, it is more useful for determining anisotropy.
- Surface hardness tests (SHR and HL) are not sufficient to determine the anisotropic properties of rocks because they are adversely affected by the properties of the rocks. On the other hand, P-wave velocity can give reliable results in practically determining anisotropy in engineering and rock mechanics studies.
- Laboratory P-wave velocity assessments considering anisotropy aspects in the restoration processes of monuments considered as cultural stone heritage can make positive contributions to the clarification of the deterioration processes in monuments.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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