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Adoption of ASTM A956-06 Leeb hardness testing standard to rock engineering applications

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ABSTRACT

The Leeb dynamic hardness test was originally developed for metallic materials and is now widely used in rock engineering and engineering geology. This study aims to fundamentally investigate the application conditions of the Leeb hardness test in rock engineering because it is a high-precision, fast, nondestructive, and portable method. Therefore, four main limitations of the Leeb method mentioned in ASTM A956-06 have been further analyzed. The important challenges, including scale effect, temperature effect, surface roughness effect, and the effect of physical properties on the Leeb method, have been studied. For this purpose, 33 rock samples with a wide range of hardness and different geology origins were used. Based on the results, the minimum thickness of the block samples of 5 *cm* (or volume of 500 cm^3) and the length-to-diameter ratio of 1.6 on core samples were suggested. Moreover, block samples were exposed to various temperatures, including −30, 0, 20, 50, 100, and 150 °*C*. The results indicated that with increasing the temperature, the Leeb hardness decreased, but the trend of the Leeb hardness variations is unnoticeable. The roughness analyses using a laser profilometer indicate that the Leeb hardness of rough samples can easily be determined with high reliability using the Leeb hardness of polished samples. Also, the Leeb hardness test for rough surfaces with *JRC* <4 (classes 1 and 2) can be used properly and performed locally in classes 3 to 10. Finally, the statistical analyses showed that the density and porosity have reasonable effects on Leeb's hardness.

1. Introduction

Hardness is one of the most important physical properties of rocks that shows its resistance against permanent deformation, scratch, and penetration [1–3]. So far, many rock hardness testing methods with different mechanisms have been provided, which are unique in terms of the variety of methods and standards among other rock properties [4]. The hardness value has a significant relationship with rock mechanical properties and geological characteristics and therefore is a suitable tool for analyzing rock machinability. From the viewpoint of an applied force by the hardness tool, the rock hardness testing methods are divided into two general classes: static and dynamic. Static hardness methods have been thoroughly investigated for use in rock engineering. Dynamic hardness methods generally involve Shore, Schmidt, and Leeb. Among dynamic methods, the Leeb (or Equotip) hardness method has been less studied and is still associated with errors.

The Leeb hardness test method has been introduced by Leeb [5] and originally has been developed for measuring the hardness of metallic materials. This test is a portable, fast, and non-destructive method. Nowadays, the Leeb device, which is provided digitally and with very small instruments for measuring the dynamic hardness of steel products under ASTM A956-06 [6], does not have an ASTM standard and an ISRM-suggested method in the field of rock engineering.

The portable use, nondestructive test, practical index for field measurement, suitability for applications in a wide range of rock hardness, applicability in a wide range of UCS (5–280 *MPa*), a great utility for core logging, and applicability in laminated/fractured shale intervals are the main advantages of the Leeb method [7–11]. Generally, nondestructive tests can be used to measure in situ surface hardness with lower impact energy [12–14]. The Leeb hardness test has also been used in geomorphology science [15–17].

Some limitations of ASTM A956-06 for the Leeb hardness test in rock mechanics have not been investigated clearly and extensively. In other words, there is still no well-established testing procedure for using the Leeb dynamic hardness test in rock mechanics. Accordingly, the current study investigated the following questions in rock engineering

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Table 1
Characteristics of the studied rocks.

Rock code	Rock name	Number of samples for each rock type	Dimensions
1	Limestone	**(I) Leeb test**(Block sample)	**(I)**
2	Fossiliferous limestone	: 7	Area: 10×10 *cm*
3	Fossiliferous limestone	**(II) Leeb test**(Core sample)	Thickness: 1,2,3,4,5,6,7 *cm*
4	Limestone	: 9	
5	Limestone		**(II)**
6	Limestone		L/D ratio:
7	limestone	**(III) Physical tests**	0.4, 0.6, 0.8, 1, 1.2,
8	Limestone	(Irregular sample)	1.4, 1.6, 1.8, 2
9	Travertine	: 1	
10	Limestone		**(III)**
11	Marble		10 rock fragments
12	Limestone	**(IV) Rockwell tests**(Block	with a minimum mass
13	Cavernous limestone	sample) : 1	of 50 *g*
14	Limestone		**(IV)**
15	Limestone		Area:
16	Cavernous limestone	**(V) Temperature**(Block sample): 6 samples for each	10 × 10 *cm* Thickness: 5 *cm*
17	Limestone	temperature	Volume: 500 cm^3
18	Cavernous limestone	(-30, 0, 20, 50, 100, and 150 °*C*)	**(V)**
19	Travertine		Area:
20	Cavernous limestone	**(VI) Tensile strength**(Core	10 × 10 *cm* Thickness: 5 *cm*
21	Limestone	surface)	Volume: 500 cm^3
22	Limestone	: 3	
23	Granodiorite		**(VI)**
24	Quartz monzonite		Diameter: 54 *mm* (NX) Thickness: 27 *mm*
25	Tuff		
26	Rhyolite		
27	Tuff		
28	Diorite		
29	Muscovite granite		
30	Granite		
31	Mylonite granite		
32	Sino-granite		
33	Tuff		

applications:

- Can the Leeb test be applied to various types of rocks?
- What is the suitable pattern of test on the rock samples?
- What is the effect of physical properties on the Leeb hardness test?
- What is the relationship between the strength of the rocks and their Leeb hardness?
- What is the effect of the surface roughness of samples on the Leeb hardness test?
- What is the effect of the surface temperature of samples on the Leeb hardness test?
- What is the relationship between the Rockwell hardness scale and the Leeb method?
- Can the Leeb test be applied with high reliability in rock and geological engineering?

To this end, this study has attempted to reduce the limitations of previous studies and to profoundly investigate all the details of this method along with answering the above questions and aims.

2. Literature review

Since 1993, some studies have been performed on applying the Leeb dynamic hardness method in rock mechanics. In the current study, the most important studies that have been presented until now have been reviewed. These studies have examined and analyzed various aspects of the Leeb hardness test, such as the prediction of UCS, the effect of specimen size, surface roughness, physical properties, weathering, etc. Verwaal and Mulder [18] have investigated the effect of core sample size with diameters of 30, 40, and 50 *mm*. Their results show that the Leeb hardness values of samples with a diameter of 50 *mm* are lower than larger samples. Okawa et al. [19] stated that the surface roughness of the samples has no clear influence on the hardness measurements. Viles et al. [13] evaluated the relationship between sample size and Leeb and Schmidt hardness in sandstone blocks with volumes ranging from 200 to 2000 cm^3. They showed that the Schmidt hammer has a significant relationship with sample volume (between 600 and 2000 cm^3). In contrast, they proposed that the Equotip device is most appropriate for samples with small volumes. Yilmaz [20] examined the effect of sample size (5, 7, 9, 11, 13, and 15 *cm*) on Leeb hardness value and stated that

Fig. 1. Overall view of collected and prepared samples.

Fig. 2. View of the Leeb instrument used in the experiments.

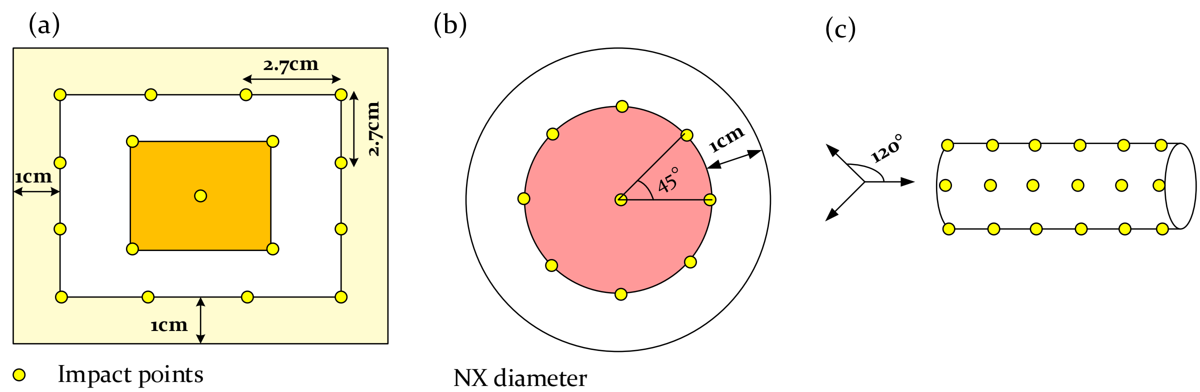

Fig. 3. Schematic of test patterns on (a) blocks (b) core surface and (c) core body.

there was no clear relationship between sample size and Leeb hardness. Wilhelm et al. [21] have studied two issues related to the Leeb hardness method. Their first result indicates that the Leeb test is appropriate for soft rocks. Additionally, they showed that the suitable sample size for testing was strongly dependent on the porosity of the rock. In more porous (heterogeneous) and weathered samples, the sample size should be larger. Corkum et al. [22] examined the variation in the Leeb hardness value in four cube samples with side lengths ranging from 25.4 to 203.2 *mm* and eight core samples with various *L/D* ratios from 0.17 to 3.52. They stated that for the block samples with a volume >90 cm^3 and core samples with *L/D* >0.4, the Leeb hardness values are independent of the scale effect. Desarnaud et al. [23] investigated the effect of different parameters such as sample size, surface roughness, and moisture content on Leeb hardness value. They suggested using samples with a minimum volume of 60 cm^3 and a minimum thickness of 13 *mm* to measure the Leeb hardness value. Their results showed no clear trends in Leeb hardness values over roughness values from 100 to 800 μm. Additionally, as moisture content significantly affects the Leeb results, the hardness values have been decreased by 26 % in comparison to the dry sandstone. Williams et al. [24] studied the effect of weathering cycles on variations of the Leeb hardness values on sandstone and found that the Leeb hardness values decrease after 6, 12, 18, and 24 weathering cycles. Çelik et al. [25] investigated the effect of the *L/D* ratio of core specimens on the Leeb hardness. They recommended a minimum volume of 110 cm^3 with a minimum diameter of 50 *mm* and a minimum *L/D* ratio of 1.5 for reliable measurements of Leeb hardness. İnce and Bozdağ [26] examined the effect of sample size on the Leeb hardness of magmatic rocks. They found that the Leeb hardness did not change after 7 *cm* of sample edge length. In addition, the regression relationships have been presented between UCS, Young's modulus, density, porosity, and V_P with the Leeb hardness. Their statistical analyses revealed that the porosity and UCS have the highest correlation coefficients with the dry and saturated Leeb hardness, respectively. Gomez-Heras et al. [27] have provided a way to estimate the UCS by combining the Leeb hardness technique with ultrasonic pulse velocity. Garrido et al. [28] predicted the UCS of limestone samples using Leeb hardness. They first heated the samples at different temperatures, including 105, 200, 300, 400, 500, 600, 700, 800, and 900 °*C*, and then cooled them in two modes, slow and quick. They provided relationships for predicting UCS in both modes with significant correlation coefficients. Benavente et al. [29] conducted a study on carbonate sedimentary rocks to estimate the UCS by combining open porosity, V_P, Leeb hardness, and micro-drilling resistance force with multiple regression expressions. Also, some studies have investigated the relationships between the Leeb hardness values and the physical and mechanical properties of rocks [8–10,18,22,25,30–36].

3. Scope of the study

The current research discusses the standardized method for determining the Leeb hardness value in rock engineering. The size effect (scale effect), physical characteristics such as porosity and density, surface roughness effect, and temperature effect of rock samples on Leeb hardness test results are considered in this process. So, the authors have attempted to provide a procedure for reliable measuring of rock hardness in laboratory conditions using precision, digital, nondestructive, and portable Leeb instrument.

4. Background of the Leeb hardness test method

In the Leeb instrument, an impact body from the diamond-tipped or tungsten carbide ball is applied to the surface of the specimen vertically. Next, the electronic indicator measured the impact and rebound velocities.

The impact and rebound velocities are accomplished with a permanent magnet mounted, which moves through a coil in the impact device and induces an electric voltage on both impact and rebound movements. These induced voltages are proportional to the respective impact and rebound velocities. The shape of this induction voltage signal, which is determined by velocity versus time curve, depends on the characteristics of the sensor coil and the permanent magnet. Leeb hardness value (L.H) is calculated by dividing the rebound velocity (V_r) by the impact velocity (V_i) as given in Eq. (1) [6]. The hardness value of the samples is in ranging from 1 to 1000. Because more energy is lost in soft rocks, the rebound velocity is lower. The most significant causes of rocks' low Leeb hardness can be attributed to their weaknesses and defects.

$$\text{L.H} = \frac{V_r}{V_i} \times 1000 \tag{1}$$

The impact energy of the Leeb instrument D-type is approximately 1/200 that of the Schmidt hammer *N*-type, and 1/66 that of the Schmidt hammer L-type. As a result, the Leeb instrument produces less damage to the tested surface [13]. The Leeb hardness test can be applied in the laboratory and the field at any angle to the rock surface [13] since the instrument uses automatic compensation for impact direction.

5. Experimental procedure

5.1. Specimen preparation

33 different rock types were initially transferred to the lab to study the size effect on the Leeb hardness test method. After that, these samples were cut into 100 cm^2 (10×10 *cm*) with a thickness of 1, 2, 3, 4, 5, 6, and 7 *cm* and a volume ranging from 100 cm^3 to 700 cm^3. Additionally, NX-diameter cores were used to prepare the core samples with the length-to-diameter ratios of 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, and 2.

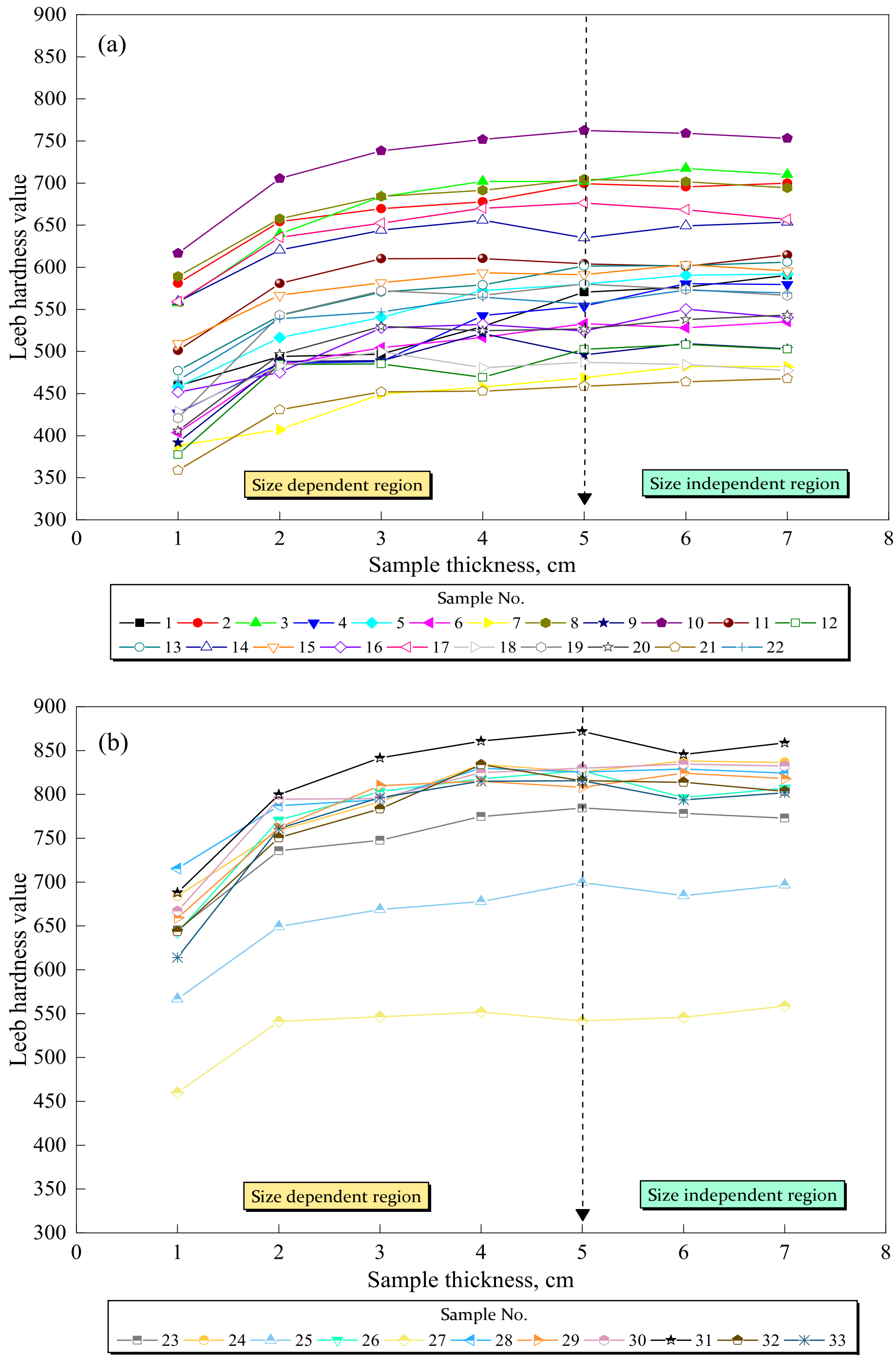

Fig. 4. The scale effect of block samples on Leeb hardness in (a) sedimentary (b) igneous samples.

These core samples were prepared under the ISRM standard, which stipulates that the samples' end surfaces be completely smooth and parallel to each other. The rock names, number of samples, and dimensions of each rock type for various experimental tests are shown in Table 1. Also, the overall view of collected and prepared samples is shown in Fig. 1.

5.2. Test procedure

In this study, the Leeb hardness of rocks was measured using the ITI-130 model (D1 + type) Leeb instrument, which is shown in Fig. 2. In the current work, Leeb tests have been performed using the patterns shown in Fig. 3. The important point is not considering 1 *cm* from each side of the block samples (see Fig. 3(a)). The reason is to minimize the impact of micro-cracks caused by rock cutting in the sample preparation phase. In core samples, both surface and body were used for testing. For the end surfaces of core samples, 1 *cm* of sample perimeter was ignored and nine impacts were applied on each surface at 45° intervals (Fig. 3(b)). Also, to test the core body, six impacts were applied to the body at 120° intervals (Fig. 3(c)). Therefore, square, circular, and rotational patterns have been used in block samples, core surfaces, and core bodies, respectively. Finally, the arithmetic mean of 17 single readings on the block samples and 18 single readings on both body and end surfaces of core samples was reported as the Leeb hardness value of samples. According to the findings of Corkum et al. [22], the convergence of Leeb hardness values is suitable between 10 and 20 readings per test.

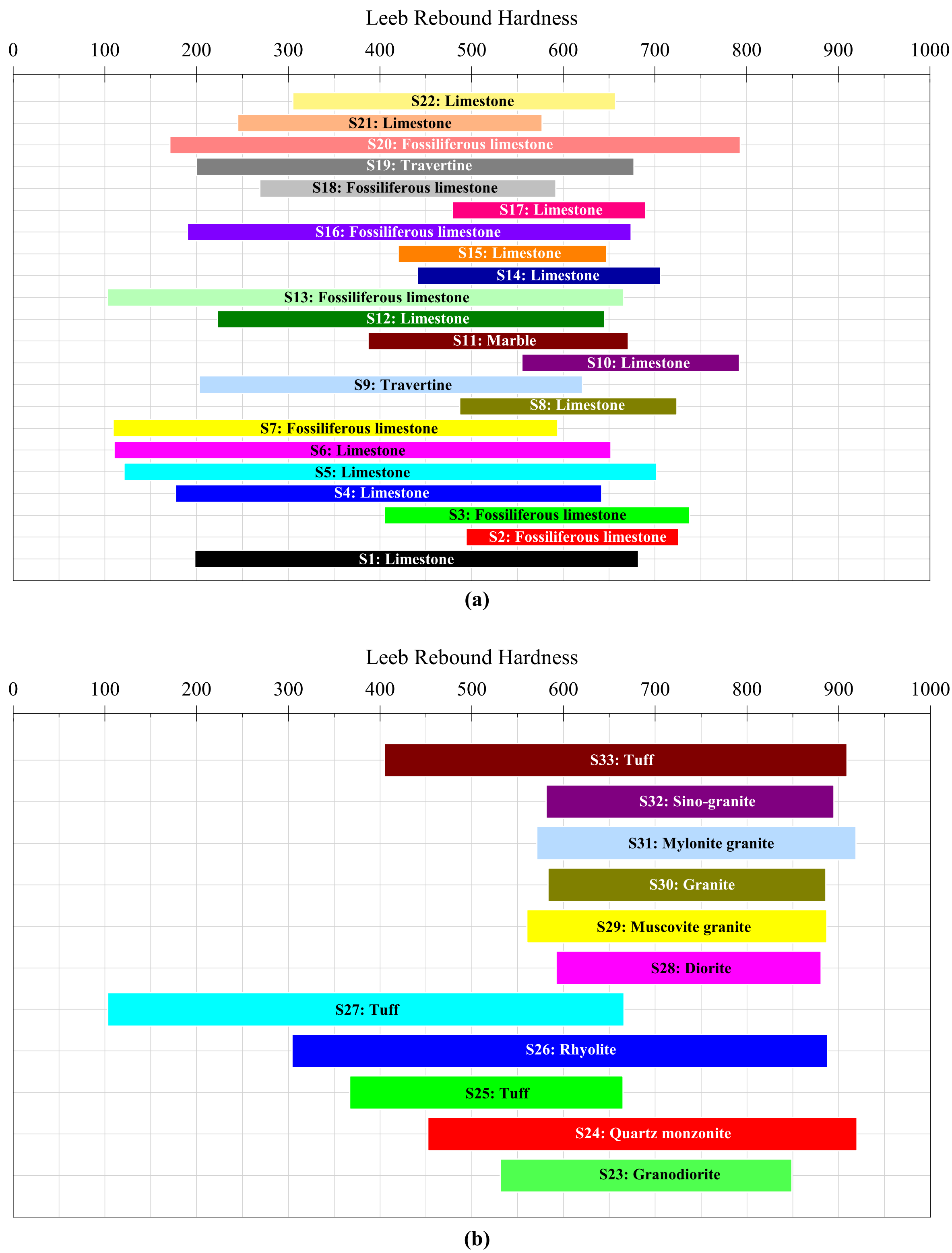

Fig. 5. Leeb hardness ranges in all thicknesses of block samples (a) sedimentary (b) igneous.

It should be noted that the surface roughness of the samples is regarded as zero in the Leeb hardness tests due to the saw cut of block samples and the polishing off the end surfaces of core samples. According to ASTM A956-06 [6], the end surfaces to be tested shall be smooth.

To reduce the vibration effects in the present study, a plastic holder under the block and core surfaces and an aluminum holder under the core body were used. According to the findings of Yilmaz and Goktan [37], the shape of the holder will not affect the results of Leeb's hardness. The main purpose of using the holder is to dampen the vibrations (albeit small vibrations) caused by the indenter of the Leeb device on the specimens.

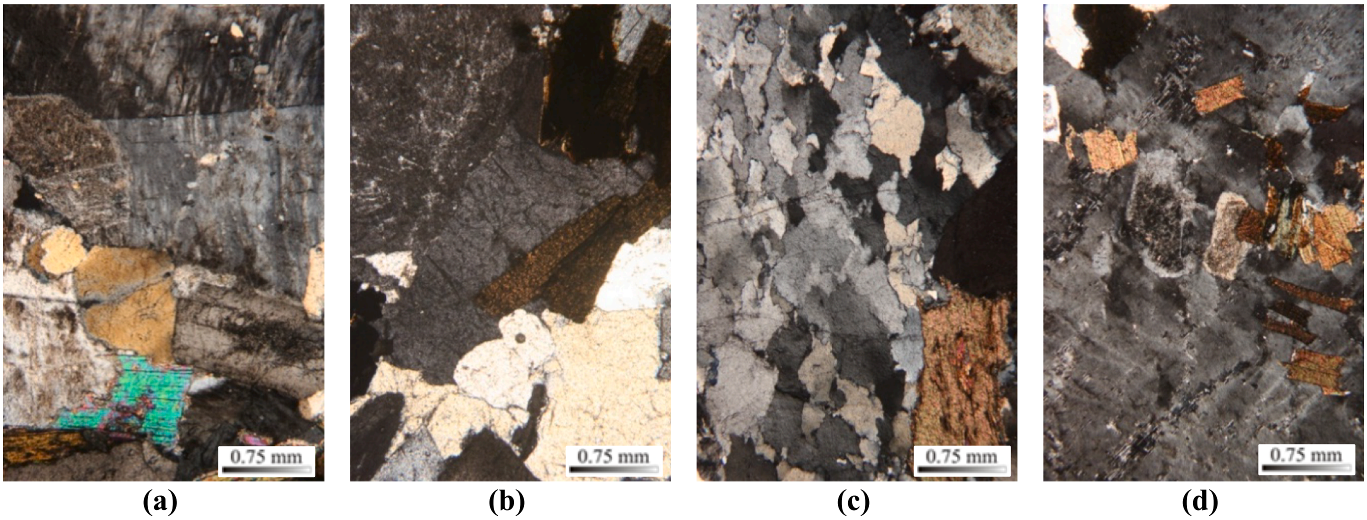

Fig. 6. Microphotographs of igneous rock samples, (a) No. 29 (b) No. 30 (c) No. 31 (d) No. 32.

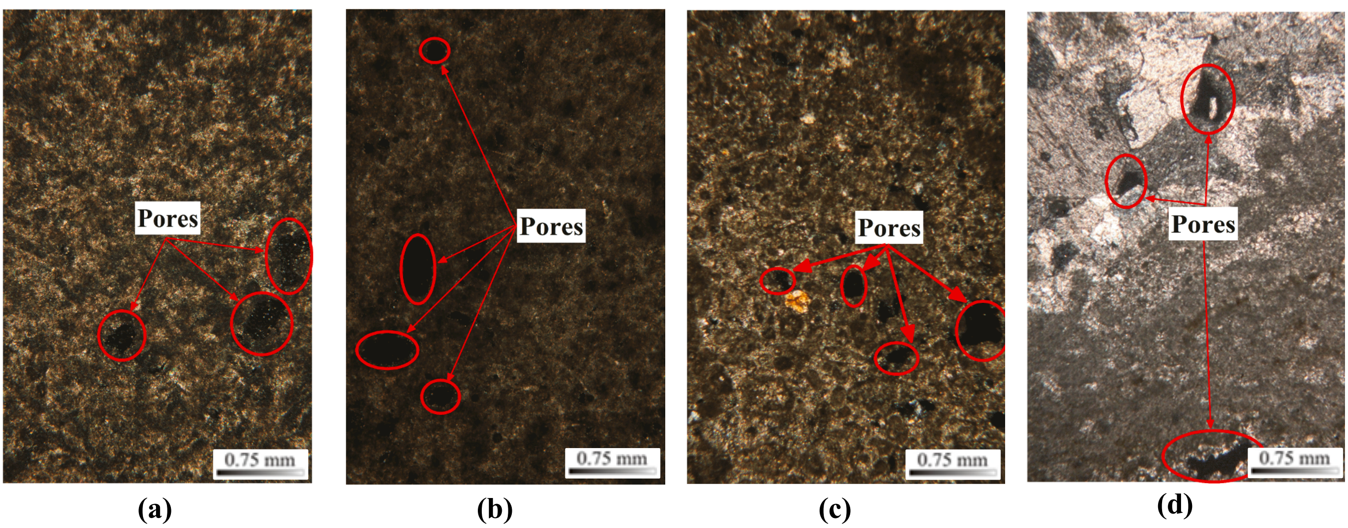

Fig. 7. Microphotographs of sedimentary rock samples, (a) No. 4 (b) No. 5 (c) No.6 (d) No. 19.

6. Laboratory testing results

6.1. Effect of thickness and volume of block samples on Leeb value

The size of the rock samples affects their properties, such as strength, stiffness, and hardness. The scale effect is the energy associated with impact testing relative to specimen mass. Having low-impact energy gives the Leeb advantages over the Schmidt hammer. But that energy and its dissipation affect the rebound velocity and thus the measured Leeb hardness values. Hence, it is expected that specimen size would impact Leeb hardness values [22].

The results of the scale effect on the Leeb hardness to determine the minimum thickness (and or critical volume) of sedimentary and igneous samples are shown in Fig. 4(a and b). According to the results, the Leeb hardness increases nonlinearly with the increase in the sample thickness. As seen in Fig. 4(a and b), after 5 *cm* of sample thickness, Leeb hardness is fixed. Also, it can be said that the minimum volume of block samples for Leeb hardness tests is 500 cm^3. Accordingly, two areas are marked on the graphs. The area before the critical thickness, where the Leeb hardness depends on the thickness (size-dependent region) and the area after the critical thickness that is independent of the thickness (size-independent region). As a vital result, Leeb hardness values were observed to be very close in both igneous and sedimentary sample groups with edge lengths between 5 *cm* and 7 *cm*. However, it was found that the Leeb hardness values generally decreased significantly by decreasing sample size with edge lengths <5 *cm* in sedimentary and igneous samples. The Leeb hardness values are determined using two test procedures: the single impact method (SIM) and the repeated impact method (RIM). In the single impact method, several individual measurements are taken at individual points within a sample area to produce a mean and standard deviation. Conversely, in the repeated impact method, several repeated impacts (successive impacts on the same location) have been taken [23]. According to the findings of Çelik and Çobanoğlu [32], the authors also believe that the best way to measure Leeb hardness is to utilize the average of the measurements taken at different points distributed on the surface of a sample. Also, due to the inherent variability of Leeb hardness values, repeated measures may not be accurate [22]. In this regard, all Leeb hardness tests for each sample size in this study were carried out with a single impact method (SIM). Eventually, the average of 17 Leeb hardness measurements taken at different points of a sample surface was found to be the best representative in block samples (see Fig. 3(a)).

The ranges of Leeb hardness values of studied block samples are shown in the forms of floating bar charts (Fig. 5(a and b)). As shown in

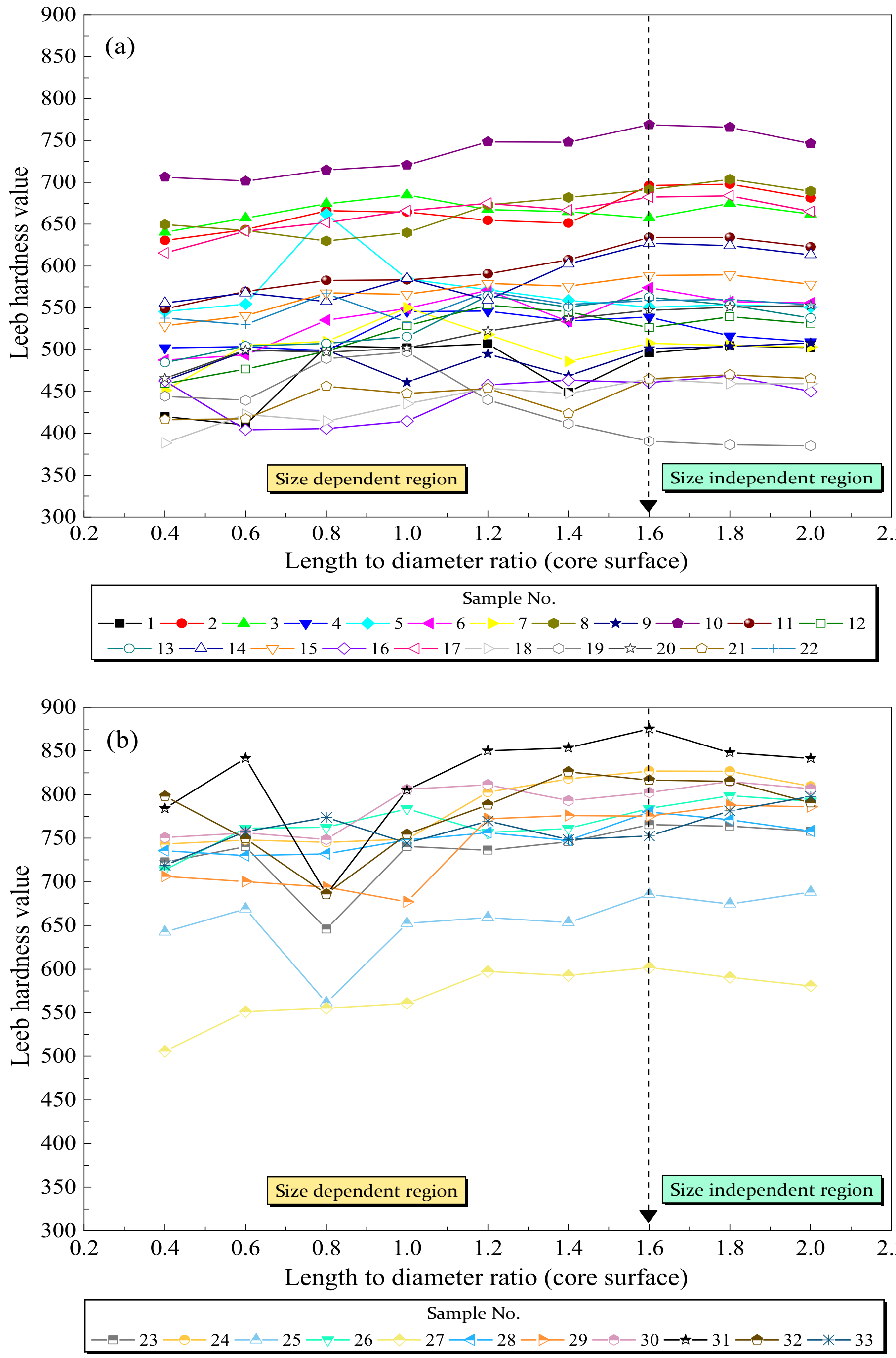

Fig. 8. Effect of length-to-diameter ratio of core samples on Leeb hardness (core surface mode) in (a) sedimentary (b) igneous samples.

these figures, various lithologies have different ranges of Leeb hardness values. This difference can be examined from three perspectives:

(1) Igneous rock samples tend to provide higher Leeb hardness values than sedimentary rock samples. Because the igneous samples absorb less energy as the ball bounces off the rock surface. In contrast, in sedimentary samples, depending on their magnitude, pores nearby the tested surfaces potentially absorb a certain amount of the exerted impact energy, which results in lower rebound values [37]. Additionally, the stress-strain curves (σ-ε) of igneous samples with higher Leeb hardness differ from sedimentary samples with lower Leeb hardness. Hence, in general, it can be said that in the igneous samples with high Leeb hardness and sedimentary samples with low Leeb hardness, the behavior of rocks like "brittle" and "ductile" respectively.
(2) The strength and stiffness of igneous samples are more than sedimentary samples, which leads to greater rebound velocity in igneous samples than in sedimentary samples. As a result, the Leeb hardness value of igneous samples is higher than the sedimentary samples.
(3) The third reason is related to the internal structure of the rock samples. Generally, in the igneous samples, the amount of porosity is less than in the sedimentary samples. Accordingly, the wave damping in the igneous samples decreases, which in turn increases the Leeb hardness. For example, four thin sections of igneous and sedimentary samples were prepared and analyzed. As seen in Fig. 6, the porosity of the igneous samples is much less

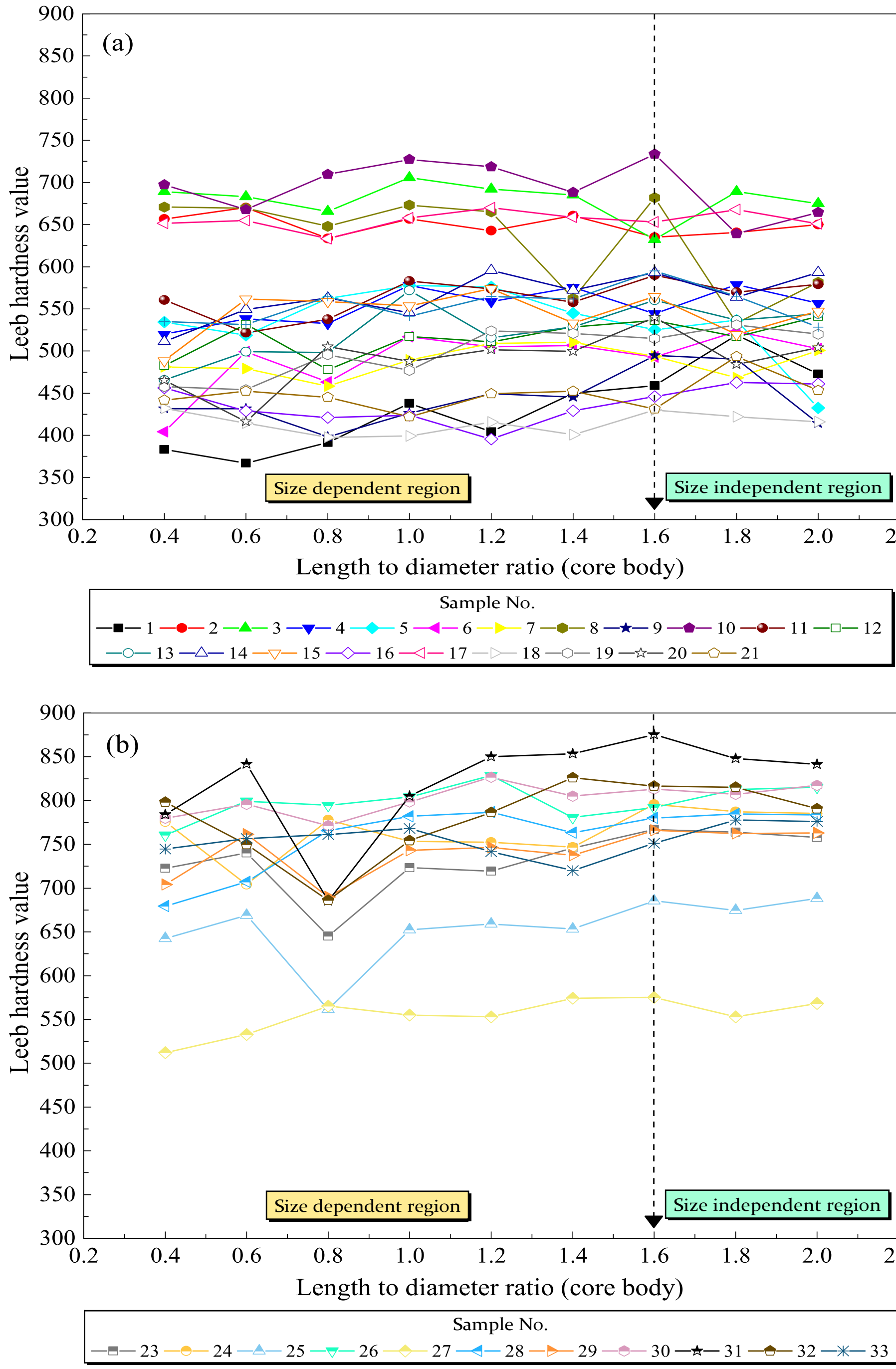

Fig. 9. Effect of length-to-diameter ratio of core samples on Leeb hardness (core surface mode) in (a) sedimentary (b) igneous samples.

than the sedimentary samples, and this texture increases the Leeb hardness of the igneous samples. In other words, fine and coarse grains of minerals such as quartz, biotite, plagioclase, and K-feldspar are the constituents of these rocks that make the rock stronger. In contrast, the pores in sedimentary samples, as shown in Fig. 7, are high, and velocity damping in these pores reduces the rebound velocity and ultimately leads to a decrease in the Leeb hardness.

One of the most important applications of small-thick stone samples is in "Stone Slab" and "Stone Tiles" in the building stone industries. In general, the thickness of the tiles and slabs is low, about 2 and 3 *cm*, respectively. The floor tiles of subways, sidewalks, airports, and generally busy environments should have minimum hardness and subsequently strength. Also, slabs are widely used in the interior of buildings, hotels, and commercial centers. Therefore, the Leeb method can be used in this type of rock samples with small thicknesses. It should be noted that according to Fig. 4, the minimum thickness required to perform the Leeb test is suggested to be 5 *cm*. But carefully in this figure, it can be seen that the process of changing the Leeb hardness starts from 3 cm. Therefore, the authors suggested a thickness of 5 *cm* to reduce the uncertainty of Leeb hardness results. Hence, in general, 3 *cm* and higher thicknesses can also be used using the Leeb method.

6.2. *Effects of L/D ratio of core samples on Leeb value*

The scale effect on core samples has also been investigated in two modes. In this regard, the Leeb tests were performed on the end surfaces

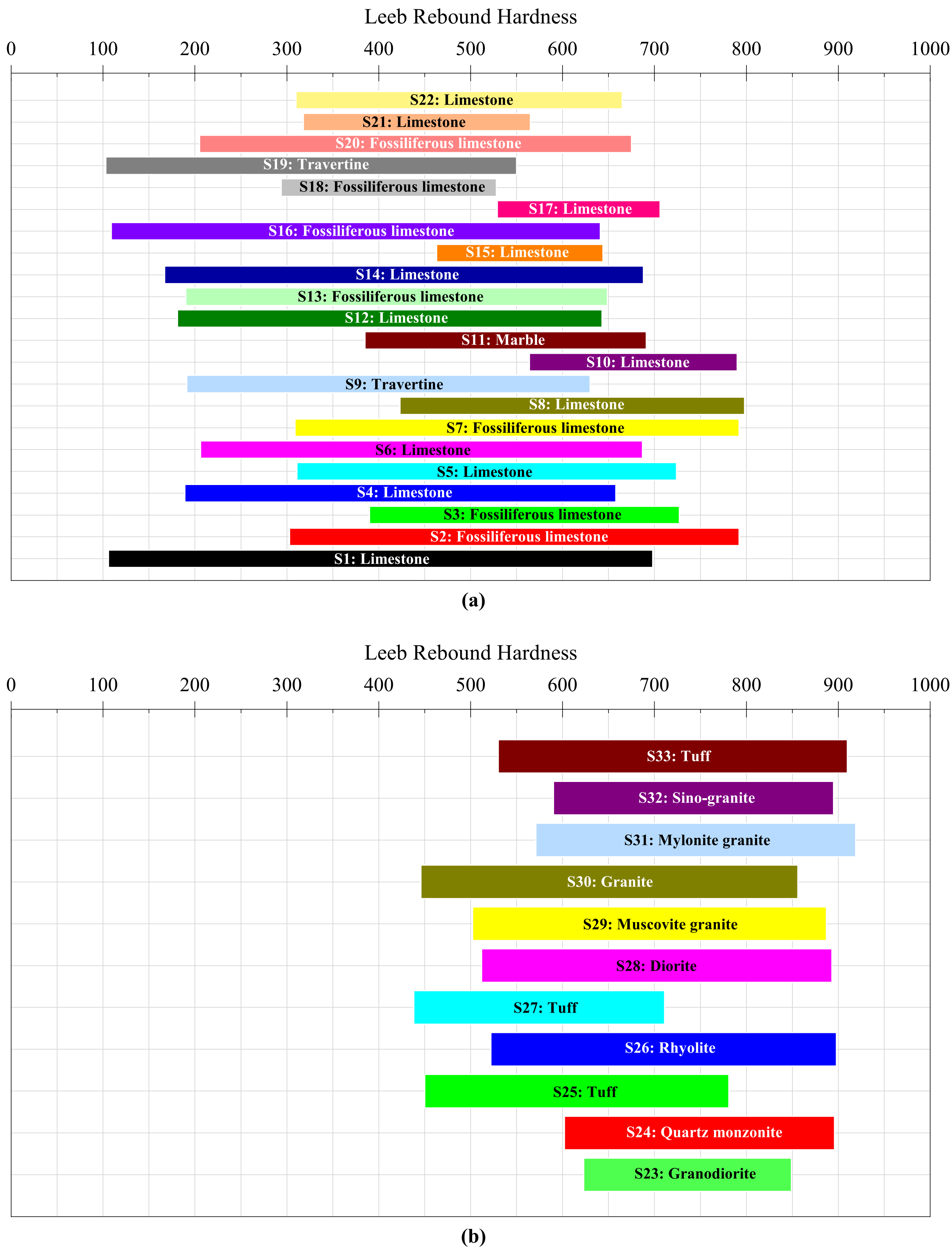

Fig. 10. Leeb hardness ranges in all thicknesses of core surface mode (a) sedimentary (b) igneous.

and the body of the samples. The results of the Leeb tests for both body and end surface modes of the igneous and sedimentary samples indicate the approximately nonlinear increasing trends of Leeb hardness with increasing *L/D* ratio (see Figs. 8 and 9). But in some samples for *L/D* <1.6, no specific trend has been observed. Also, from the *L/D* >1.6 or $V_{critical} \approx 198\ cm^3$, the curve is fixed. The important point about core specimens compared to block specimens is that the increase in Leeb hardness for block specimens is more significant than that of core specimens in both body and end surface modes. In other words, the slope of the curve related to the size-dependent region for block samples is

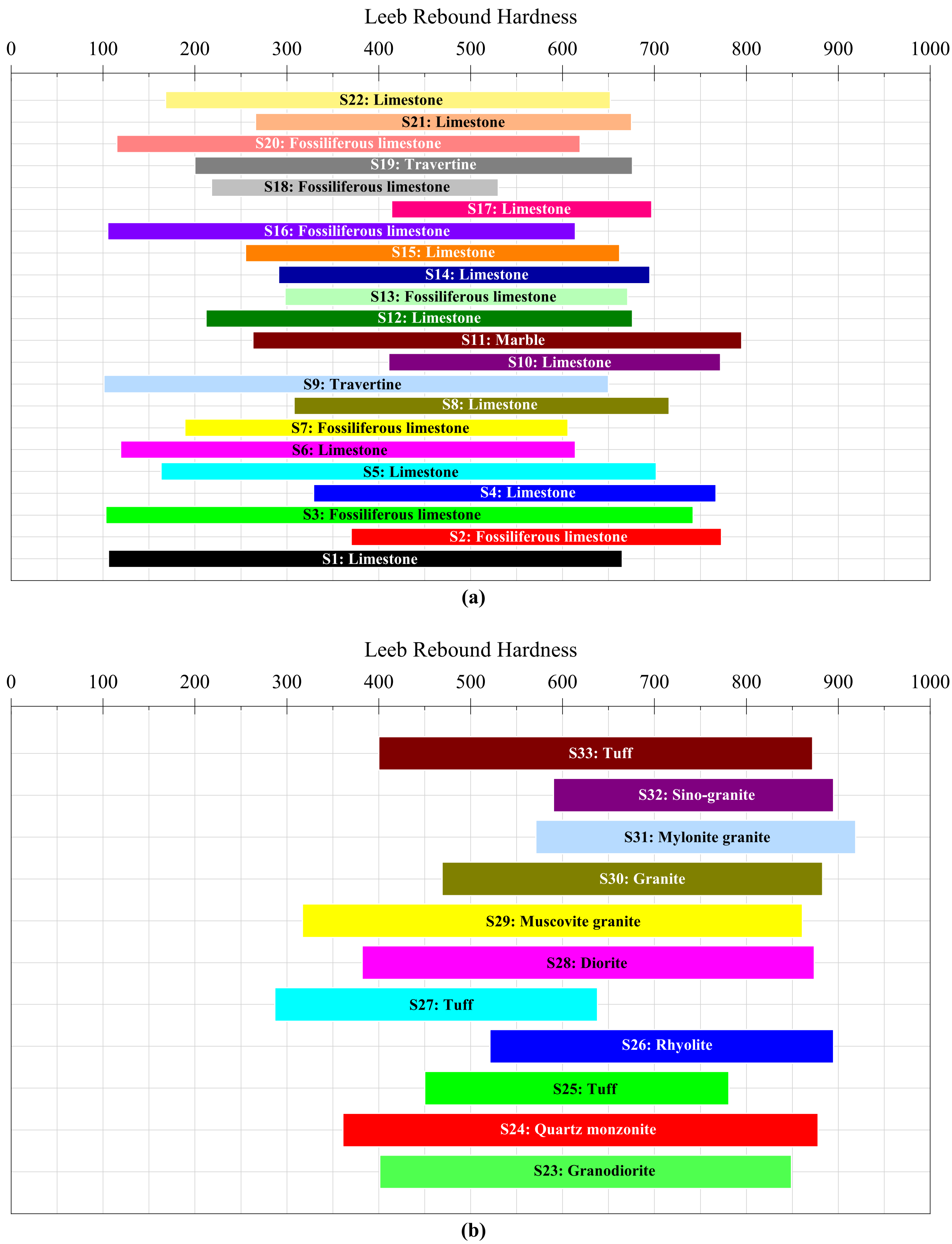

Fig. 11. Leeb hardness ranges in all thicknesses of core body mode (a) sedimentary (b) igneous.

more than the core samples. Also, based on Figs. 8 and 9, the increasing trend of Leeb hardness values relative to size for block samples is more apparent than that of core samples. Therefore, it can be concluded that block samples are more sensitive to scale effect than core samples. Moreover, the scattering of results of the core body has been observed more than on the core surface. Therefore, in the rock hardness tests with the Leeb method, first, the block samples and later the surface of core samples are sensitive to the scale effect. Comparing the range of Leeb hardness values in three modes of block sample, core surfaces, and core body in igneous rock samples (Fig. 5(b), Fig. 10(b), and Fig. 11(b))

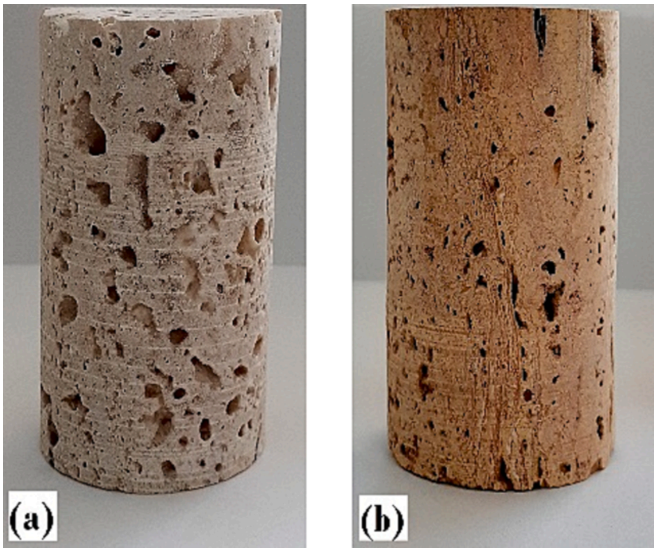

Fig. 12. The pores on the sample surface, (a) sample No.1 (b) sample No.9.

shows that the numerical range of Leeb hardness of core surfaces mode converges more to the right of the graph. Additionally, as shown in Fig. 11, the range of Leeb hardness values is more significant in the core body mode in both sedimentary and igneous samples. This mode is more inclined to lower values compared to block and core surfaces modes. However, Figs. 5 and 10, and (11) can be very useful guides to the Leeb hardness values of different types of rock samples.

The scattering of Leeb hardness values of some rock samples shown in Fig. 9(a) is related to the high porosity of those samples. The scattering in the core samples is higher than in the block samples. Therefore, it can be said that according to the finding of Yilmaz [20] and Çelik and Çobanoğlu [32], the Leeb hardness method has a problem in high porosity samples. In the case of porous rocks, when the indenter impacts near the sample's pores, the device sometimes gives an error and may occur test fail. Therefore, it is necessary to be careful with this type of rock during the test. In other words, the range of uncertainty of the Leeb hardness value is vast in high porosity samples.

For further analysis, thin-section microphotographs were prepared and studied on two samples of studied sedimentary rocks with large pores on the surface of the rock sample. When the Leeb hardness test was performed on the pores of the surfaces of samples 1 and 9 (Fig. 12), the Leeb device gives an error. In this study, Optical Microscope techniques were also applied to evaluate the pores of the specimens in Leeb dynamic hardness tests. As shown in Fig. 13, the samples have large pores on their textures. The pores on the sample surface may have on the hardness test that the ball inside the device tube may not turn back perpendicularly and could touch the tube sides (friction), resulting in the reduced height of the ball rebound [38].

Additionally, in some igneous samples, the Leeb hardness values in the L/D of 0.8 have decreased sharply (Figs. 8 and 9). According to the tests conducted in the laboratory, some Leeb tests have been performed on coarse grains and some on fine grains in the body and surfaces of the core samples. Therefore, the main reason for the decrease in the Leeb hardness in the L/D ratio of 0.8 is related to the grain size in the texture of the rock samples. Considering that 18 tests were performed on the body and the surfaces of the core samples, some tests were inevitably performed on coarse grains (such as quartz grains) and others on fine grains (such as biotite grains). Therefore, it is expected that the Leeb hardness values in rocks with coarse grains will be higher than in rocks with fine grains.

In most rock mechanics research, core samples are used to analyze rock properties in the laboratory. This is due to the ease of preparation of the core samples. Accordingly, it is necessary to investigate the relationship between the Leeb hardness of critical block samples (5 *cm*) and the critical surface and body of the core samples ($L/D = 1.6$). As seen in Figs. 14 and 15, block and core samples have linear correlations with a high coefficient of correlations (R^2). Therefore, to perform the Leeb hardness test in rock mechanics experiments, core samples with $L/D \geq 1.6$ can be used. As are used from core samples with different "*L/D*" ratios based on ISRM and ASTM standards for measuring physical and mechanical properties, including uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), V_P, V_S, and point load strength tests.

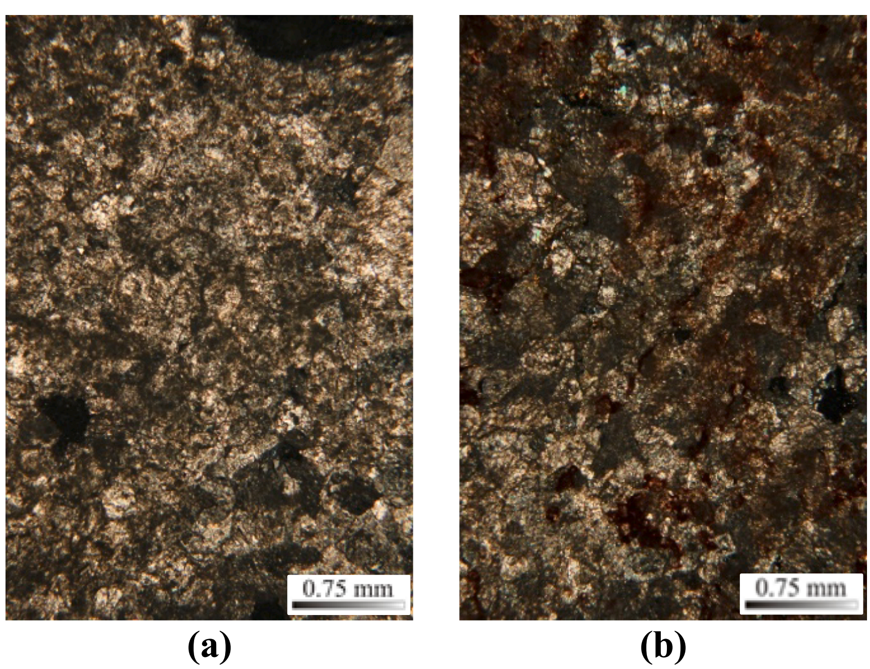

Fig. 13. Microphotographs of (a) sample No. 1, (b) sample No. 9.

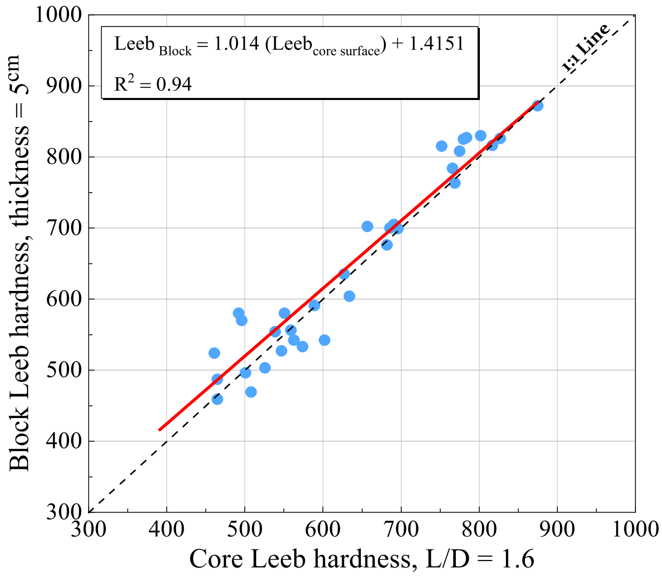

Fig. 14. Relationship between the Leeb hardness of block samples with the core surface of samples.

6.3. Relationships between the physical properties and Leeb dynamic hardness

The study of the physical properties of intact rocks is very important in civil and mining engineering works [39]. The fundamental relationships between porosity and density with Leeb hardness have been clarified due to the importance of physical properties in rock mechanics applications. In the current research, the physical properties of the rock samples, including the density (g/cm^3) and porosity (%) were determined using ISRM [40]. The results of the physical tests and Leeb hardness tests on the block samples, core surface, and core body are listed in Table 2.

In order to investigate the relationships between porosity and density with Leeb hardness, linear, power, exponential, and logarithmic regression analyses were tried. The most reliable empirical equation was determined based on the highest R^2 and lowest standard error of the estimate (*SEE*). The equation of the best-fit line (95 % confidence level) and the correlation coefficient were calculated for each equation.

General trends of regression curves are shown in Figs. 16 to 19. In regression analyzes, igneous and sedimentary samples were entered separately into statistical analyzes. As can be seen in these figures, the Leeb hardness has decreased and increased with increasing porosity and density, respectively. These trends have been obtained in three modes of tests (block, core surface, and core body). Based on the results, reasonable trends are observed between the parameters and the Leeb hardness. There are exponential and logarithmic relationships between the Leeb dynamic hardness scale with the porosity of the igneous and sedimentary samples, respectively. Conversely, the relationships between Leeb hardness with density in igneous and sedimentary samples follow power and exponential functions, respectively. Additionally, the most remarkable effects of porosity and density on Leeb hardness are observed in the block and core surface modes, respectively. In other words, depending on the type of the Leeb hardness test mode (block samples or the end surfaces and body of core samples), the effect of the porosity and density is different. These relationships are not very strong based on R^2, but the main purpose of regression analyses is to show the effect of the porosity and density on the Leeb hardness. These trends indicate that other parameters may have a greater effect on Leeb's hardness. While it is a complex task to quantitatively determine the simultaneous influence of all the parameters involved [37]. One of the most influential parameters on the Leeb hardness is the strength of the rocks. In many studies [10,22,26,33,37], the relationship between UCS and Leeb hardness of various rocks have been studied and the results

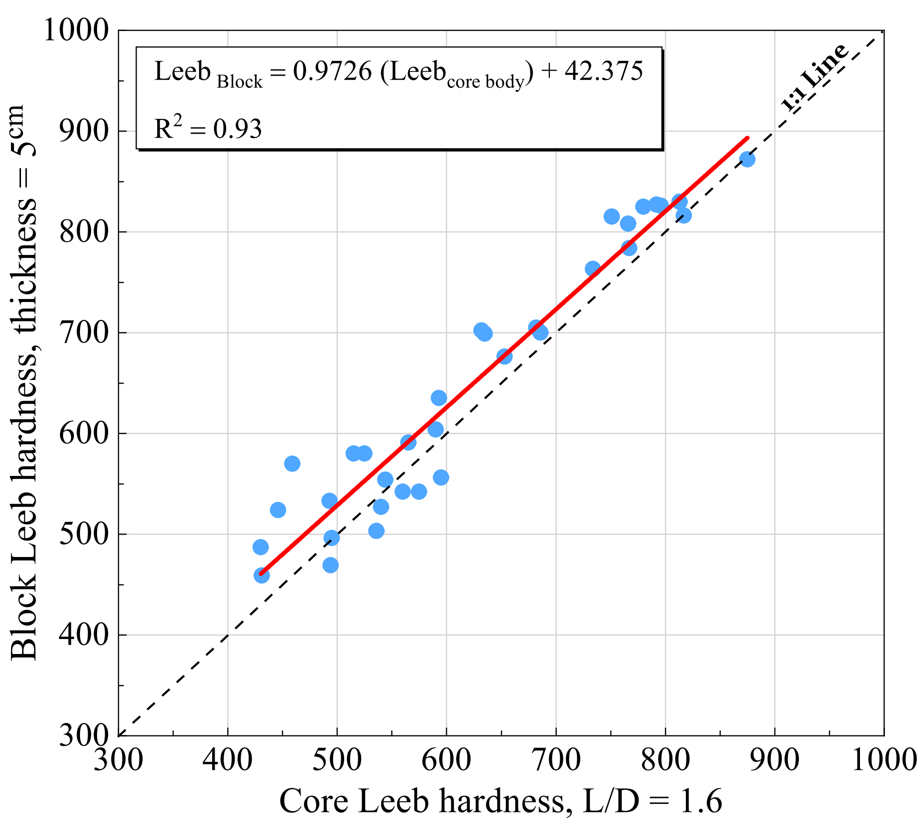

Fig. 15. Relationship between the Leeb hardness of block samples with the core body of samples.

Table 2
Physical properties and critical values of Leeb hardness for tested rocks.

Sample No.	Rock name	Density (g/cm^3)	Porosity (%)	LH (block-5 cm)	LH (core-surface)	LH (core-body)
1	Limestone	2.46	2.21	570	496	459
2	Fossiliferous limestone	2.59	0.79	699	696	635
3	Fossiliferous limestone	2.64	1.16	702	657	632
4	Limestone	2.46	1.84	554	539	544
5	Limestone	2.54	6.31	580	551	525
6	Limestone	2.54	2.52	533	574	493
7	limestone	2.40	6	469	508	494
8	Limestone	2.63	0.9	705	691	682
9	Travertine	2.42	6.39	496	501	495
10	Limestone	2.64	0.19	763	769	734
11	Marble	2.59	4.43	604	634	590
12	Limestone	2.47	7.04	503	526	536
13	Cavernous limestone	2.58	2.68	542	563	560
14	Limestone	2.52	1.93	635	627	593
15	Limestone	2.59	7.25	591	589	565
16	Cavernous limestone	2.50	3.51	524	461	446
17	Limestone	2.63	0.43	676	682	653
18	Cavernous limestone	2.46	6.06	487	465	430
19	Travertine	2.50	3.90	580	492	515
20	Cavernous limestone	2.50	3.68	527	547	540
21	Limestone	2.32	8.61	459	465	431
22	Limestone	2.59	1.41	556	559	595
23	Granodiorite	2.72	0.56	784	766	767
24	Quartz monzonite	2.77	1.13	826	827	796
25	Tuff	2.59	3.46	700	686	686
26	Rhyolite	2.78	2.39	827	784	792
27	Tuff	2.39	5.48	542	602	575
28	Diorite	2.70	0.76	825	780	780
29	Muscovite granite	2.58	1.31	808	775	766
30	Granite	2.73	1.26	830	802	813
31	Mylonite granite	2.82	0.87	872	875	875
32	Sino-granite	2.60	1.33	816	817	817
33	Tuff	2.67	2.29	815	752	751

show a very close relationship between these two parameters. Also, the grain size and texture of rocks have a significant effect on Leeb's dynamic hardness.

6.4. Relationship between tensile strength with Leeb hardness of rock samples

One of the important applications of the portable and non-destructive Leeb method is in predicting other mechanical parameters, such as the tensile strength (σ_t) of rocks. In other words, using the quick Leeb method, the tensile strength of rocks can be estimated both in the laboratory and in the field. In this study, the tensile strength of samples was measured based on ISRM [40]. It should be noted that to measure the tensile strength of rocks, at least three core samples with a diameter of 54 *mm* and a thickness of 27 *mm* were prepared and tested in accordance with ISRM [40]. The average values obtained as the tensile strength of rocks are shown in Fig. 20.

After measuring the tensile strength of the rock samples, the relationships between the Leeb hardness and the tensile strength of the samples were investigated using regression analysis. As can be seen in Figs. 21 and 22, the relationships between the Leeb hardness and tensile strength in sedimentary and igneous rock samples follow logarithmically and power functions, respectively. It should be noted that regression analyzes were performed in all three modes of block samples, body,

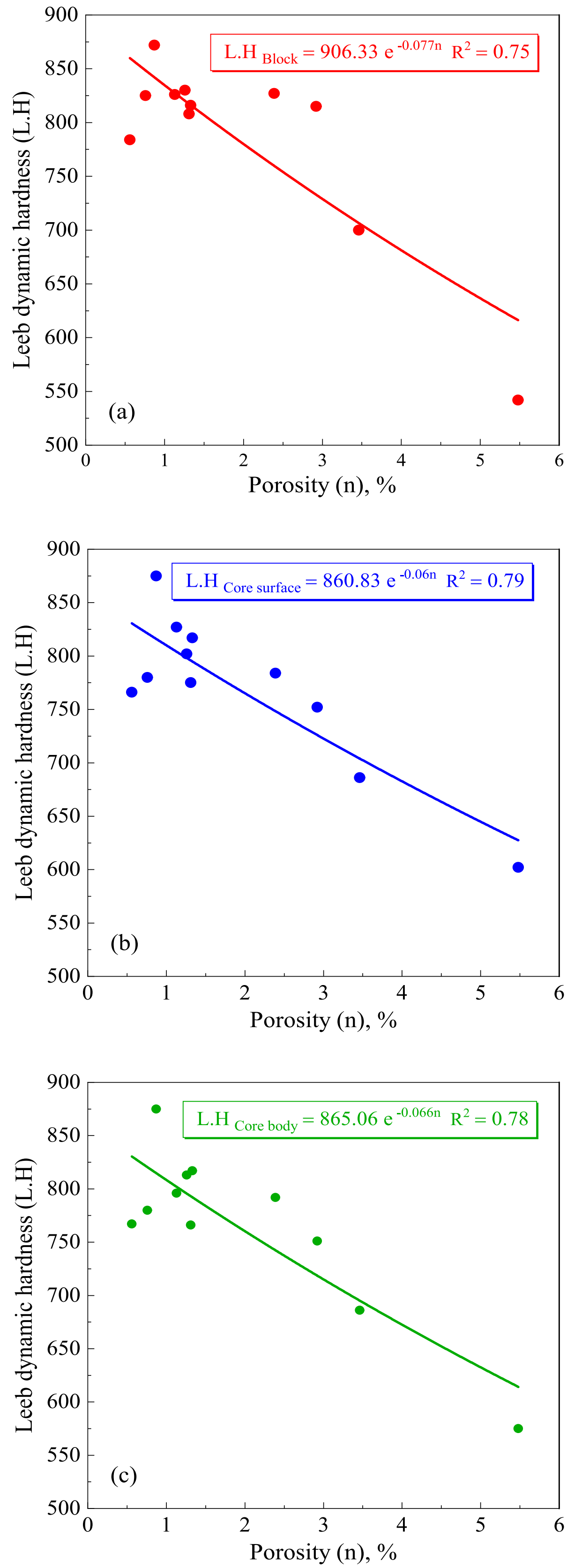

Fig. 16. Relationship between porosity and Leeb hardness value in igneous samples for various sample modes (a) block (b) core surface (c) core body.

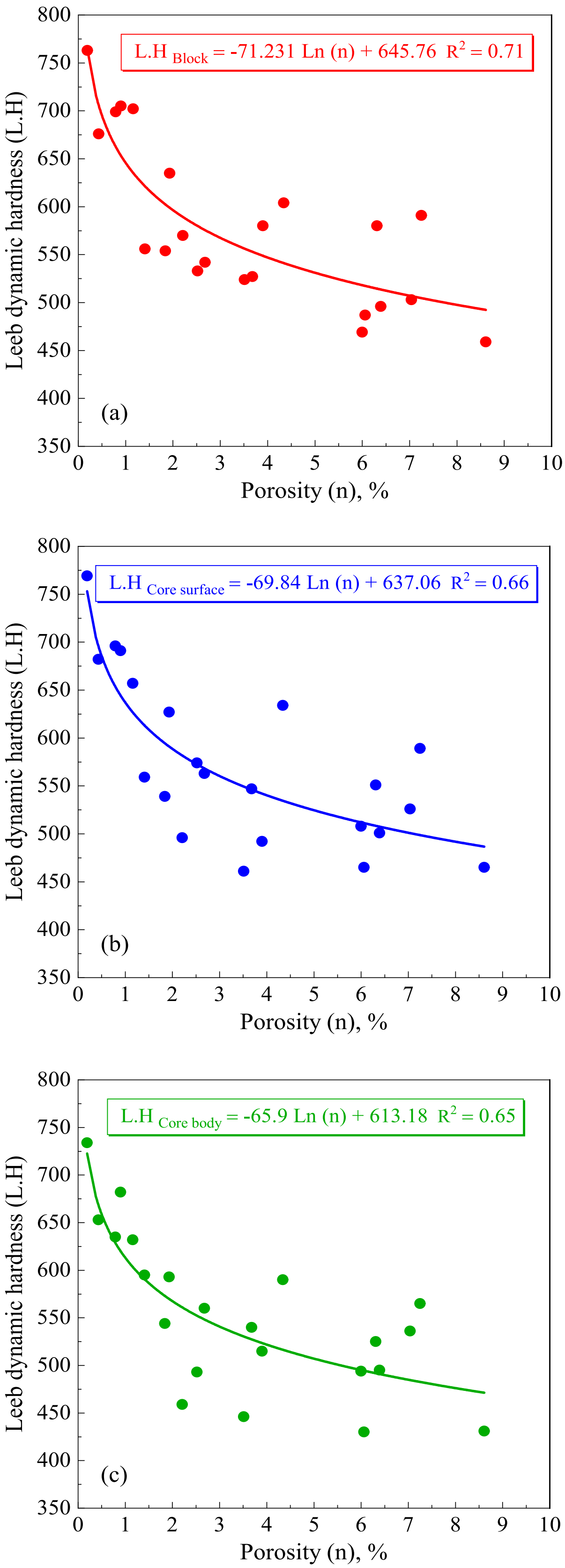

Fig. 17. Relationship between porosity and Leeb hardness value in sedimentary samples for various sample modes (a) block (b) core surface (c) core body.

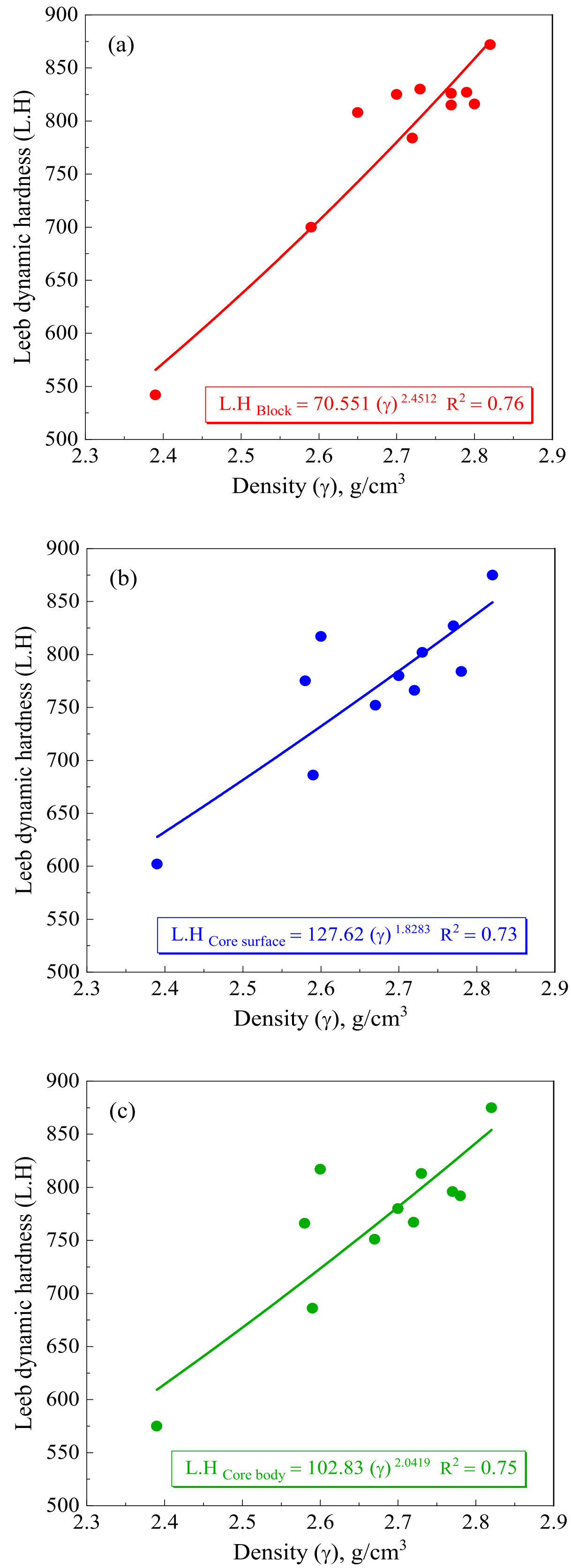

Fig. 18. Relationship between porosity and Leeb hardness value in igneous samples for various sample modes (a) block (b) core surface (c) core body.

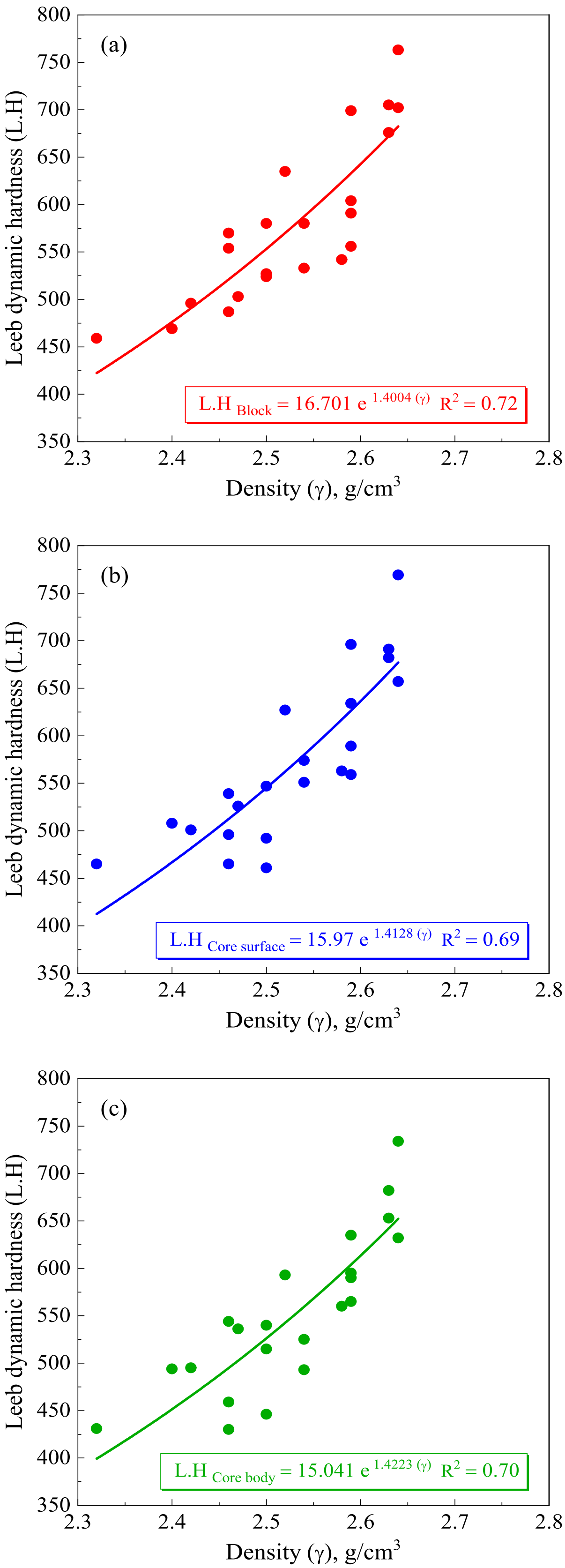

Fig. 19. Relationship between porosity and Leeb hardness value in sedimentary samples for various sample modes (a) block (b) core surface (c) core body.

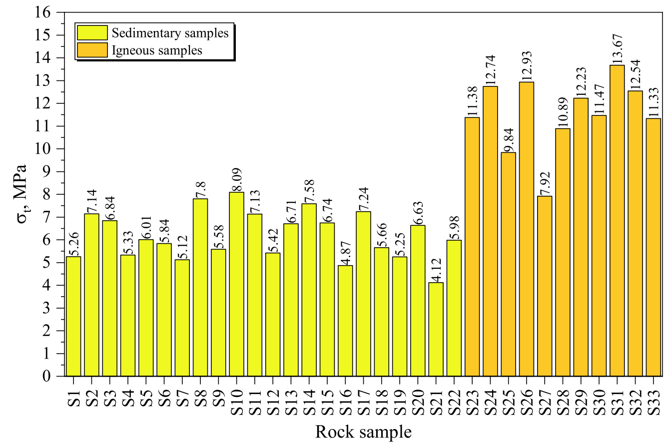

Fig. 20. Tensile strength values of studied rock samples.

and surfaces of core samples. In addition, according to Figs. 21 and 22, in sedimentary and igneous samples, the relationships between the Leeb hardness of the core surfaces and the tensile strength have the highest correlation coefficients. Therefore, based on the obtained results, it is possible to predict the tensile strength of the rocks in three modes of the samples with high reliability of the Leeb hardness.

6.5. Relationship between Rockwell hardness scale with Leeb hardness

One of the main applications of the portable Leeb method is its use in predicting other traditional hardness testing methods. For this purpose, in this research, the relationship between Vickers and Rockwell methods with Leeb's hardness was analyzed in 33 rock samples. Hence, the block samples of the dimensions of $10 \times 10 \times 5$ *cm* were tested by an advanced universal hardness testing machine, KB Prüftechnik (Fig. 23). In some samples, several tests on different points of rock surfaces were carried out, and the average of the three precise tests was assigned as the Vickers hardness value. All tests were run at a load level of 50 *Kgf* (*HV50*). The mean values of the measured Vickers hardness for the studied rocks.

On the other hand, according to ASTM E140 – 12b [41], other hardness traditional scales can be related to Leeb hardness. Therefore, after measuring the Vickers hardness (*HV*), the equivalent Rockwell hardness values (*HRB*) of the rock samples were also determined using Eq. (2). Table 3 shows the Vickers and Rockwell hardness values for the studied samples.

$$HRB = 1.14665E+02 + 8.82795E\text{-}02(HV)\text{-}1.41855E\text{-}04(HV)^2\text{-}6.69528E+03(HV)^{-1} \quad (2)$$

Based on statistical analysis, the relationships between Leeb hardness and Rockwell hardness in sedimentary and igneous rock samples follow logarithmic and exponential functions, respectively (Fig. 24). In other words, it is possible to estimate the Rockwell hardness with a good approximation using the Portable Leeb method.

6.6. Effect of the surface temperature of rock samples on Leeb hardness

One of the most important and influential factors in the results of the Leeb hardness test is the surface temperature of the samples. According to ASTM A956-06 [6], the temperature of the metal materials should be in the range of 4 °*C* to 38 °*C*. But for non-metallic materials such as rocks, further analysis should be done on how the temperature of the sample affects the Leeb hardness results.

In this study, the effect of various temperatures, including −30, 0, 20, 50, 100, and 150 °*C*, on variations in the Leeb hardness values are investigated. For this purpose, 33 block samples with optimal

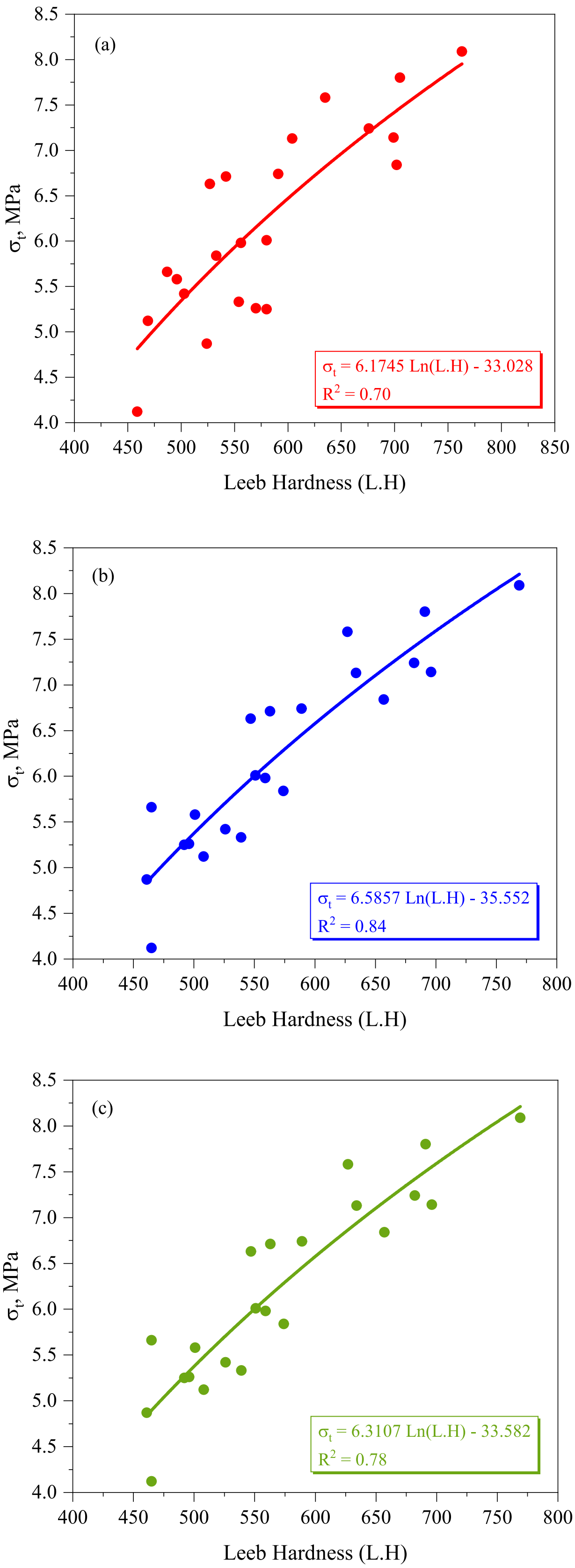

Fig. 21. Relationship between tensile strength and Leeb hardness value in sedimentary samples for various sample modes (a) block (b) core surface (c) core body.

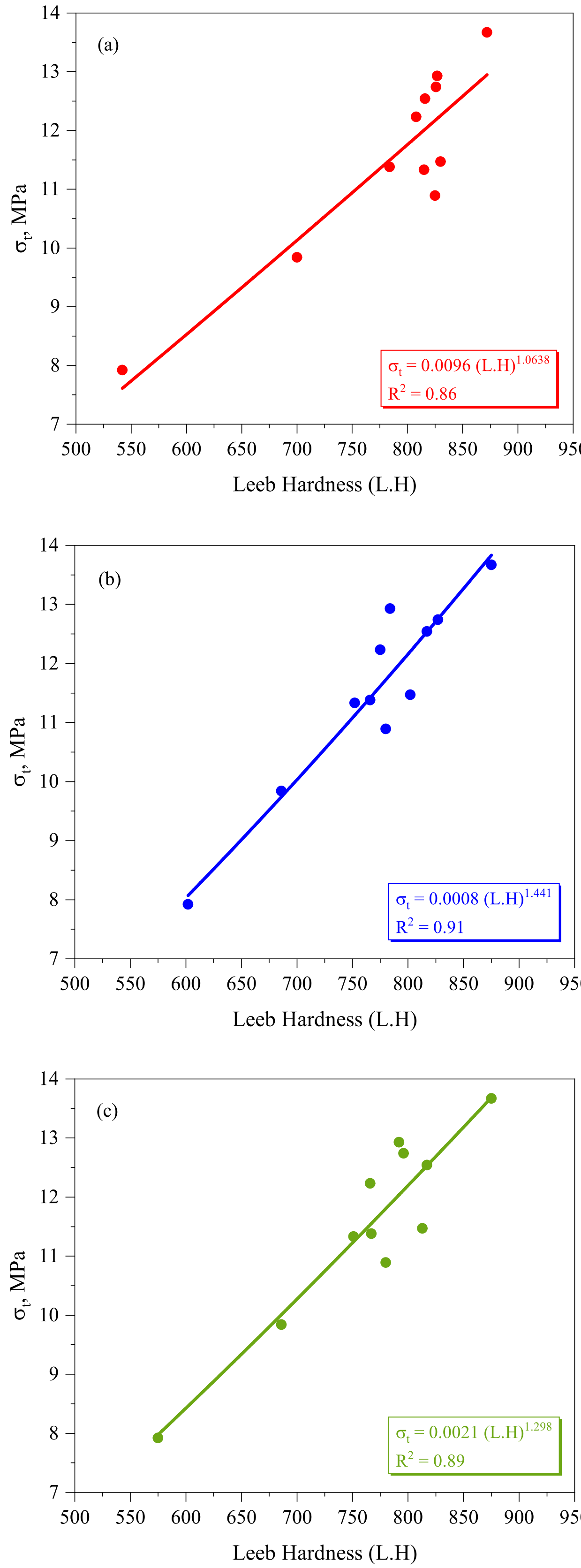

Fig. 22. Relationship between tensile strength and Leeb hardness value in igneous samples for various sample modes (a) block (b) core surface (c) core body.

Fig. 23. Applied universal hardness testing machine for measuring Vickers and Rockwell hardness values.

Table 3
Physical properties and critical values of Leeb hardness for tested rocks.

Sample No.	Rock name	Vickers	Rockwell
1	Limestone	100.6	55.5
2	Fossiliferous limestone	121.7	68.3
3	Fossiliferous limestone	150	80.1
4	Limestone	102	56.5
5	Limestone	135.3	74.5
6	Limestone	104.7	58.4
7	limestone	81.9	39.2
8	Limestone	181.3	89.1
9	Travertine	79.2	36.2
10	Limestone	145.8	78.6
11	Marble	124.8	69.8
12	Limestone	81.8	39.1
13	Cavernous limestone	79.6	36.7
14	Limestone	96.6	52.6
15	Limestone	86.6	43.9
16	Cavernous limestone	73	28.7
17	Limestone	123.9	69.4
18	Cavernous limestone	70.4	25
19	Travertine	82.7	40.1
20	Cavernous limestone	79.9	37
21	Limestone	72	27.3
22	Limestone	87.7	45
23	Granodiorite	122	68.5
24	Quartz monzonite	217	96.3
25	Tuff	92	48.8
26	Rhyolite	305.8	106.5
27	Tuff	85.6	43
28	Diorite	245	100.45
29	Muscovite granite	112.5	63.3
30	Granite	174.7	87.5
31	Mylonite granite	293.7	105.6
32	Sino-granite	281.7	104.5
33	Tuff	158.7	82.9

dimensions (thickness of 5 *cm* or volume of 500 cm^3) were placed in the oven and freezer at different temperatures. It should be noted that the heating rate of the samples was 2 °*C*/min. The samples were heated and cooled in a single cycle. In other words, all samples were subjected to different temperatures for 24 h during a heating and cooling cycle. It is also important to note that the samples were slowly cooled after each heat cycle to prevent micro-cracks that would alter the results of the Leeb hardness tests.

The surface temperature of the specimens immediately after the treatment was recorded using the IR thermometer camera model FLIR TG165 (see Fig. 25). The surfaces of the specimens were scanned by an IR thermometer and the average temperatures were automatically recorded. As shown in Fig. 25, the temperature distribution at the sample surfaces is uniform. The reason why the temperature distribution at the sample surfaces in the Leeb test must be uniform is that the Leeb hardness is a measure of the surface hardness of the materials. Additionally, because 17 impacts are applied to the entire surface of the sample, there must be a uniform distribution of temperature to investigate the effect of surface temperature on the Leeb test.

As can be seen in Figs. 26 and 27, the low-temperature variations of rock surfaces do not make a significant difference in the Leeb hardness values of sedimentary and igneous samples. But the general trends show a decrease in the Leeb dynamic hardness with increasing surface temperature. In other words, with an increasing temperature from −30 °*C* to 150 °*C*, the Leeb dynamic hardness decreases with a gradual slope. Based on the obtained results, it can be said that in the studied igneous and sedimentary samples, the most changes in the Leeb hardness for the applied temperatures were 7 % and 10 %, respectively. In contrast, the variations in the Leeb hardness of the rock sample due to high temperatures are observed due to variations in the internal structure and texture of the rock. The results of the effect of low temperatures on the Leeb hardness are consistent with the results of studies by Garrido et al. [28]. Garrido et al. [28] found that the Leeb hardness values of limestone samples had significant changes at temperatures higher than 700 °*C*. But at temperatures below 700 °*C*, changes in the Leeb hardness occur slowly and with a small slope. As a result, in this study, Leeb hardness changes occur gradually at low temperatures in a wide range of rock samples. Therefore, in general, it can be concluded that there are no significant changes in the Leeb hardness at low temperatures. But at high temperatures, due to the decrease in the strength of the rocks, the hardness also decreases.

6.7. *Effect of the surface roughness of rock samples on Leeb hardness*

Various rock samples with different mineralogical, physical, and mechanical characteristics were used to demonstrate the effects of surface roughness on the Leeb dynamic hardness values. For this purpose, 16 irregular samples were collected from different quarries and were prepared for the laboratory tests and the roughness assessment. The studied rocks include three types of tuff, eight types of limestone, one type of marble, and four types of granite.

6.7.1. *Measurement of surface roughness*

Roughness represents the height of the unevenness as compared to the perfect and ideally smooth surface and emerges as a consequence of the work of a tool deployed [42] in machining and finishing [43]. There are various parameters of roughness, such as arithmetic roughness average (R_a) and root-mean-square value (R_{rms}) that can be extracted using a laser profilometer. But the main purpose of this study is to investigate and measure the R_a.

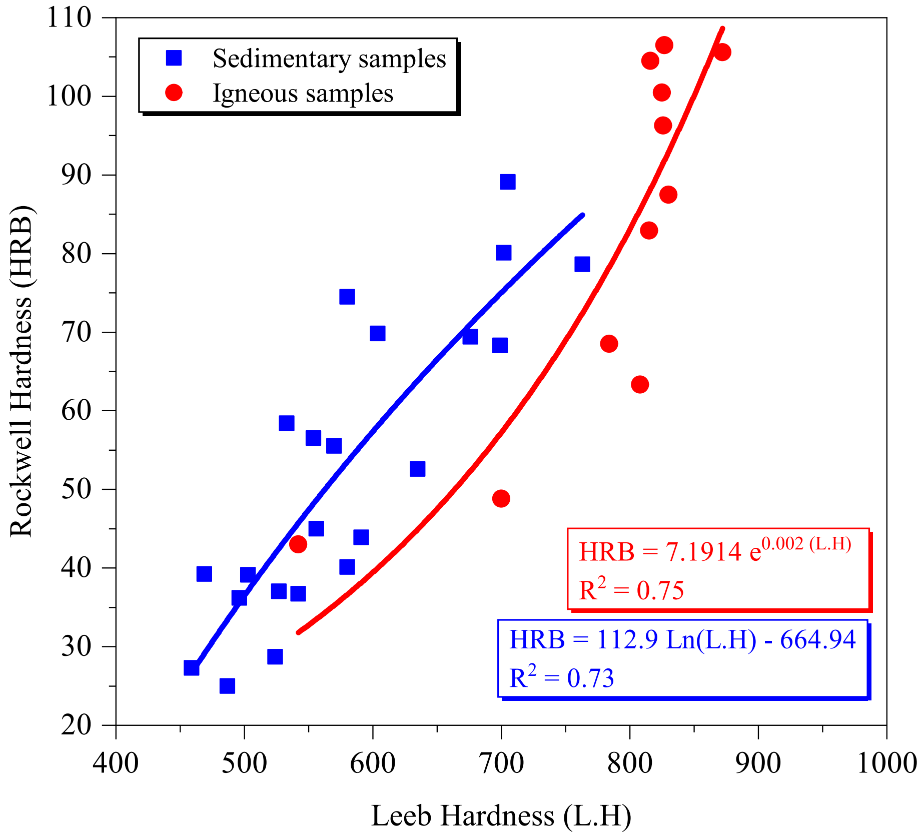

Fig. 24. Correlation between Leeb hardness and Rockwell hardness of studied rocks.

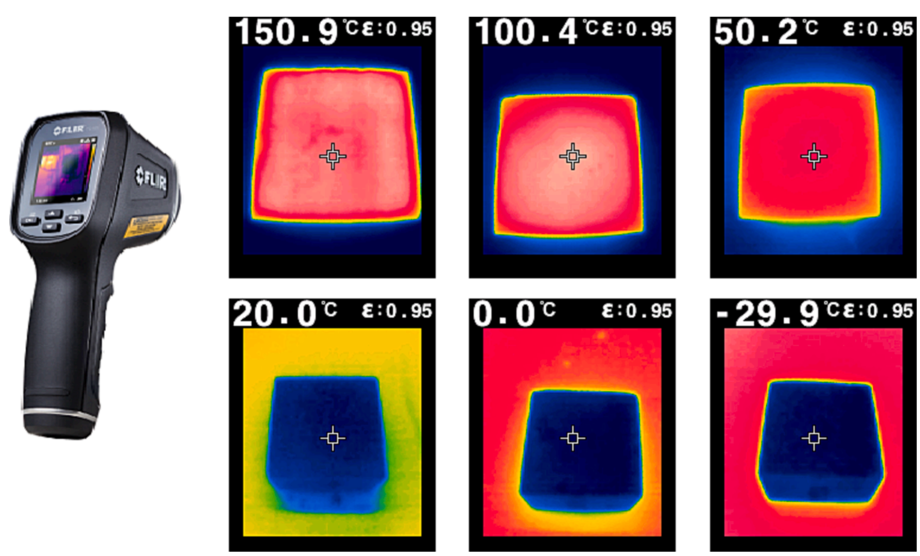

Fig. 25. The IR thermometer camera used in this study.

Roughness is measured by the height of the irregularities concerning an average line. These measurements are usually expressed in micrometers or microinches. In most cases, the arithmetic average, R_a, is used. In terms of the measurements, the R_a would be calculated according to Eq. (3) [44]. A typical roughness profile that includes the mentioned parameters is shown in Fig. 28.

$$R_a = \frac{\sum_{i=1}^{n} y_i}{n} \tag{3}$$

Where y_i is the vertical distance from the centerline and n is the total number of vertical measurements taken within a specified cutoff distance.

The surface roughness of rock samples was measured using a Laser Profilometer Model LPM-D roughness tester (Fig. 29(a)). This device measures surface profile with a triangulation laser, optical system, and CCD sensor. The laser light hits the object's surface and by using where this light is reflected after the impact on the sensor, the distance to the object can be calculated (see Fig. 29(b)). The software is developed in a way that data acquisitions are set with selected steps. Steps between two continuous data acquisitions can have 3 μm to several millimeters of

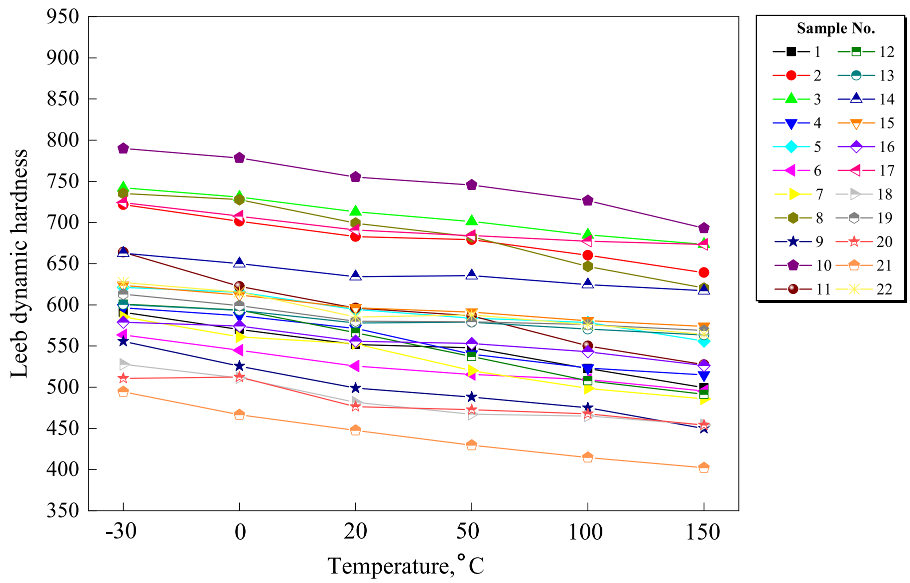

Fig. 26. The effect of surface temperature on the Leeb dynamic hardness of sedimentary samples.

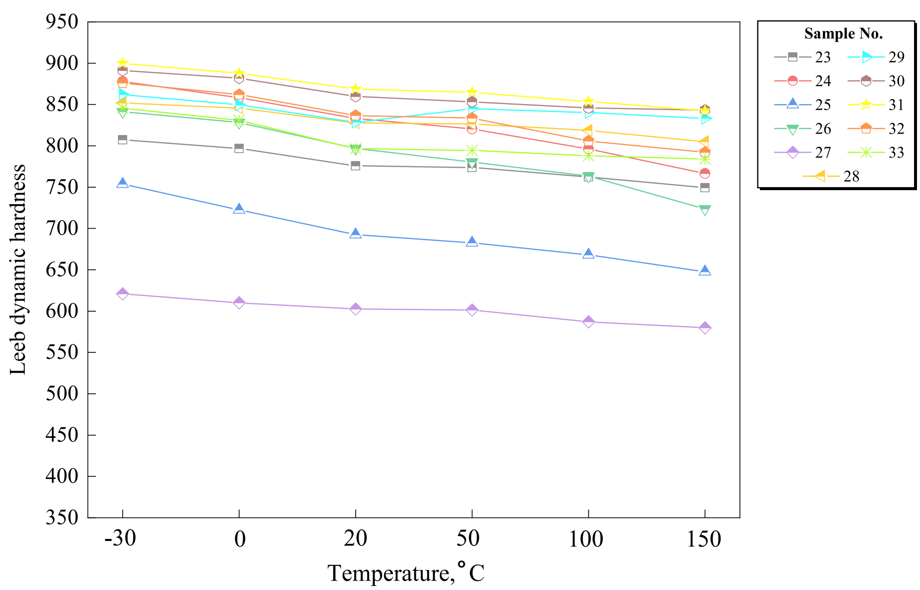

Fig. 27. The effect of surface temperature on the Leeb dynamic hardness of igneous samples.

accuracy in the two movement axes. With a shorter step, more details and accuracy are achieved; however, the time to scan the whole surface increases. The sample is installed on a stage that moves on a single axis. On the other hand, the sensor moves on a vertical axis concerning the sample. The combination of both axis movements scans the whole surface. According to mechanical limitations, the method's precision is up to 2 μ*m*.

16 samples with dimensions of 10×10 *cm* have been used to investigate the effect of varying degrees of surface roughness on Leeb hardness measurements. Data were obtained in 100 selected areas from the sample surface (1×1 *cm*). For a more accurate measurement of roughness values in each rock sample, a movement step of 0.1 *mm* is considered. The R_a data are extracted from the measurements made by the laser profilometer. An example of the grid on the rock surface is shown in Fig. 30. The statistical parameters of extracted roughness values such as maximum, minimum, average, median, and standard deviation are listed in Table 2. Moreover, histograms of the R_a for each rock sample are shown in Fig. 31. As shown in Table 2 and Fig. 31, the roughness values of all studied samples are less than about 1.5 μ*m*.

To perform the Leeb rebound test, 16 samples were prepared with rough surfaces and the Leeb hardness test was performed on them. Also, to determine the correlation between the Leeb hardness of the polished and rough surfaces, the Leeb tests were performed on the polished surfaces of the same rocks. The statistical results of the Leeb hardness measurements of polished and rough surfaces are presented in Table 3.

6.7.2. Experimental results

The roughness concept is one of the most important parameters that are effective in measuring all dynamic hardness methods, such as Schmidt, Shore, and Leeb. In the Leeb hardness tests, the surfaces to be tested shall be smooth. Failure to provide an adequate surface finish will produce questionable test results. It is recommended that the test surface

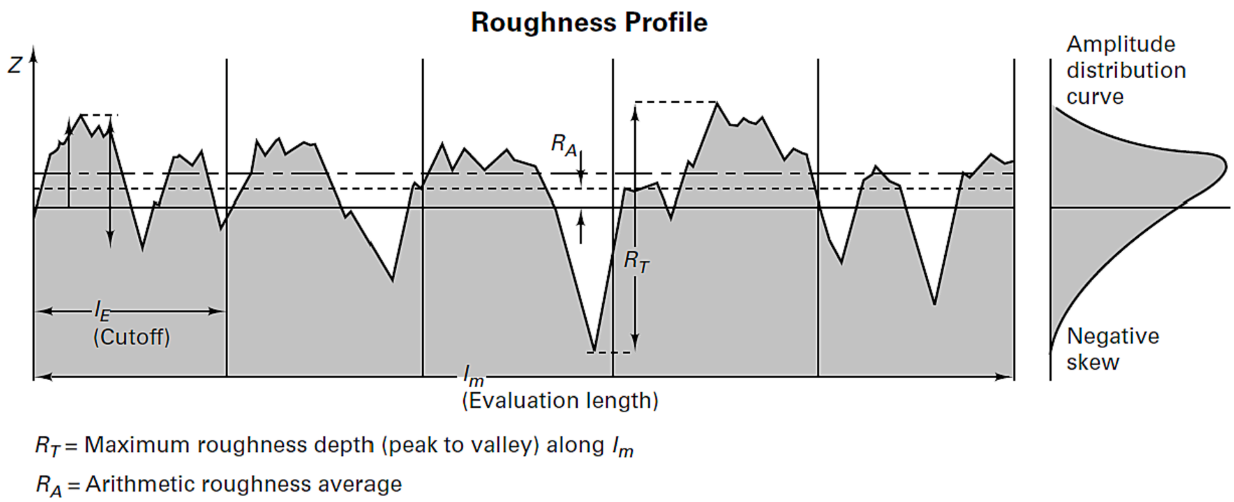

Fig. 28. A typical roughness profile with roughness parameters [44].

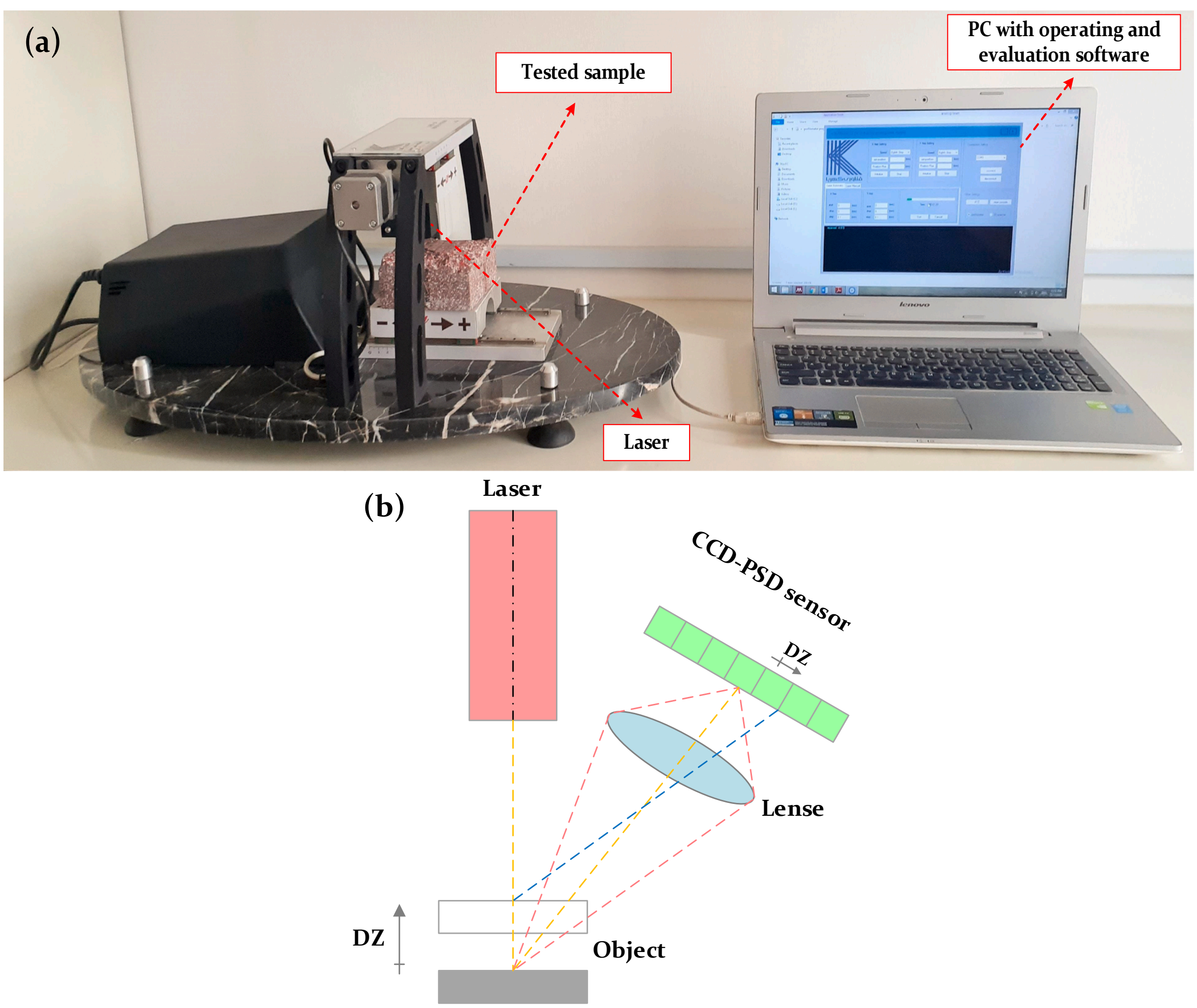

Fig. 29. Laser profilometer model LPM-D (a) view of laser profilometer (b) measurement schematic.

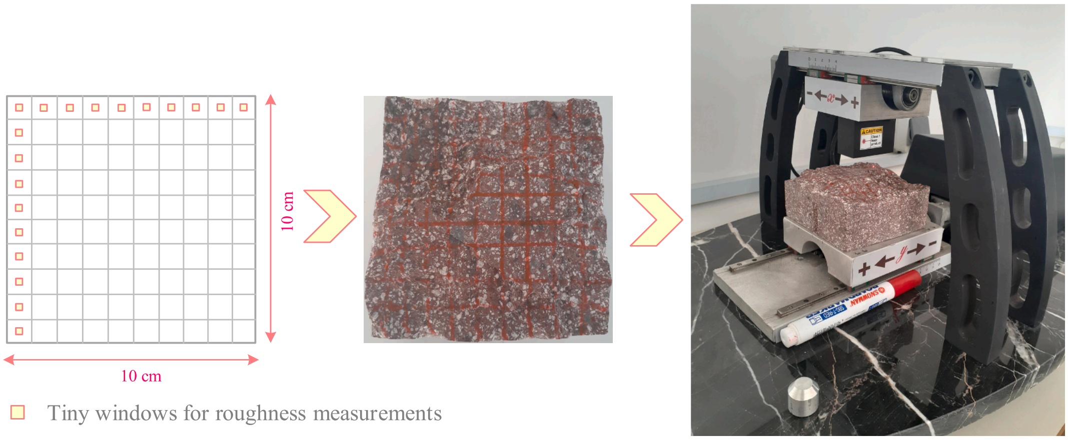

Fig. 30. Roughness measurement grid on the rock sample surface.

be machined or ground and polished [6]. Therefore, according to ASTM A956-06 [6], the surface must be free of roughness. For this reason, the conditions for using the Leeb hardness test in rough rocks should be analyzed in detail.

Studies on the effect of roughness on the results of Leeb hardness have been performed in two steps. First, the application of the Leeb device in rough samples has been studied geometrically according to Barton's roughness profile [45]. For this purpose, the acceptable classes for performing the Leeb test have been examined depending on the diameter of the Leeb device tip and the roughness depth of each Barton's roughness profile (see Fig. 32). As shown in Fig. 32, classes 1 and 2 are acceptable for hardness testing on rough specimens. Because on more rough surfaces, the Leeb instrument does not seat on the surface properly and the test gets an error. Therefore, according to these points, the Leeb hardness test for rough and irregular rock with JRC $<$ 4 can be appropriately used in total. However, the Leeb hardness test can be performed locally on profiles of classes 3 to 10. In general, it is possible to perform the Leeb hardness in rock samples with profiles similar to classes 1 and 2, as well as locally in some places of classes 3 to 10.

After determining how to use the Leeb test on rough surfaces, the Leeb hardness values of the rough and polished surfaces of the samples were measured. Accordingly, the arithmetic roughness average (R_a) values of the surfaces of each sample were measured using a laser profilometer. Then, the relationship between the Leeb hardness of rough and polished surfaces was determined using statistical analyses. Moreover, the allowable values of R_a were analyzed and established.

Leeb test on rough surfaces was performed in places of the samples where the device did not make an error. In other words, Leeb testing can also be done on rough surfaces, but points should be selected that have less roughness. Based on the Leeb hardness values of all samples (Table 3), the correlation between the Leeb hardness values of rough and polished samples was investigated. A significant correlation between them was obtained and presented in Fig. 33. This relationship was given in linear function with an R^2 of 0.95. The proposed regression equation will be very useful and can be utilized for general use. In other words, using the proposed equation, the Leeb hardness of rough samples can be predicted from polished samples with considerable accuracy in practice.

The final purpose of the current study is to investigate the effect of roughness values on the Leeb hardness and to determine the allowable R_a for Leeb testing in rock samples. The maximum allowable surface roughness depends on the test method used and the force applied. Getting the best results from Leeb hardness testing of metallic materials in rough surfaces requires 2 μ*m*/80 μ*inch* (ISO N7 R_a), but more studies are needed in rock samples.

The following steps were performed to further investigate these objectives in rock materials. To scan the surfaces of the samples from windows with dimensions of 10×10 *mm* were examined. An example of an extracted profile from the center of sample No. 1 with the roughness parameters is shown in Fig. 34. Roughness profiles can be extracted from the sample surfaces in each measured window. Also, Fig. 35 shows the three-dimensional representation of the studied sample surfaces using a laser profilometer. Based on the measured data by the profilometer, which is also presented in Table 2, the maximum surface roughness of the studied stone samples is 2 μ*m*. In general, it can be concluded that in studied rock samples for values R_a $<$ 2 μ*m*, the Leeb hardness test (D-type) can be used properly without any errors.

Generally, in the building stone industry almost all samples are being prepared by cutting with sawing discs. Hence, the roughness of building stones can be considered as zero. On the other hand, according to the results of the current study, it was found that the Leeb test can be used for samples with a roughness of$<$2 and in classes 1 and 2 of Barton's classification. Therefore, the Leeb hardness test has the potential to contribute to the applications of building stone industries. Additionally, nowadays, the Leeb method a widely used in the field of natural stones for the following reasons:

- Very low impact energy and nondestructive nature of the test
- Small and portable digital instrument
- Quick and easy hardness measurement

7. Conclusions

The Leeb hardness is a precision, digital, nondestructive, and portable method. This test measures the dynamic hardness of materials and it is widely used in rock engineering applications. The main purpose of the current study is to investigate the applicability of the Leeb method, which is an adjunct to the ASTM A956-06 to be used in rock

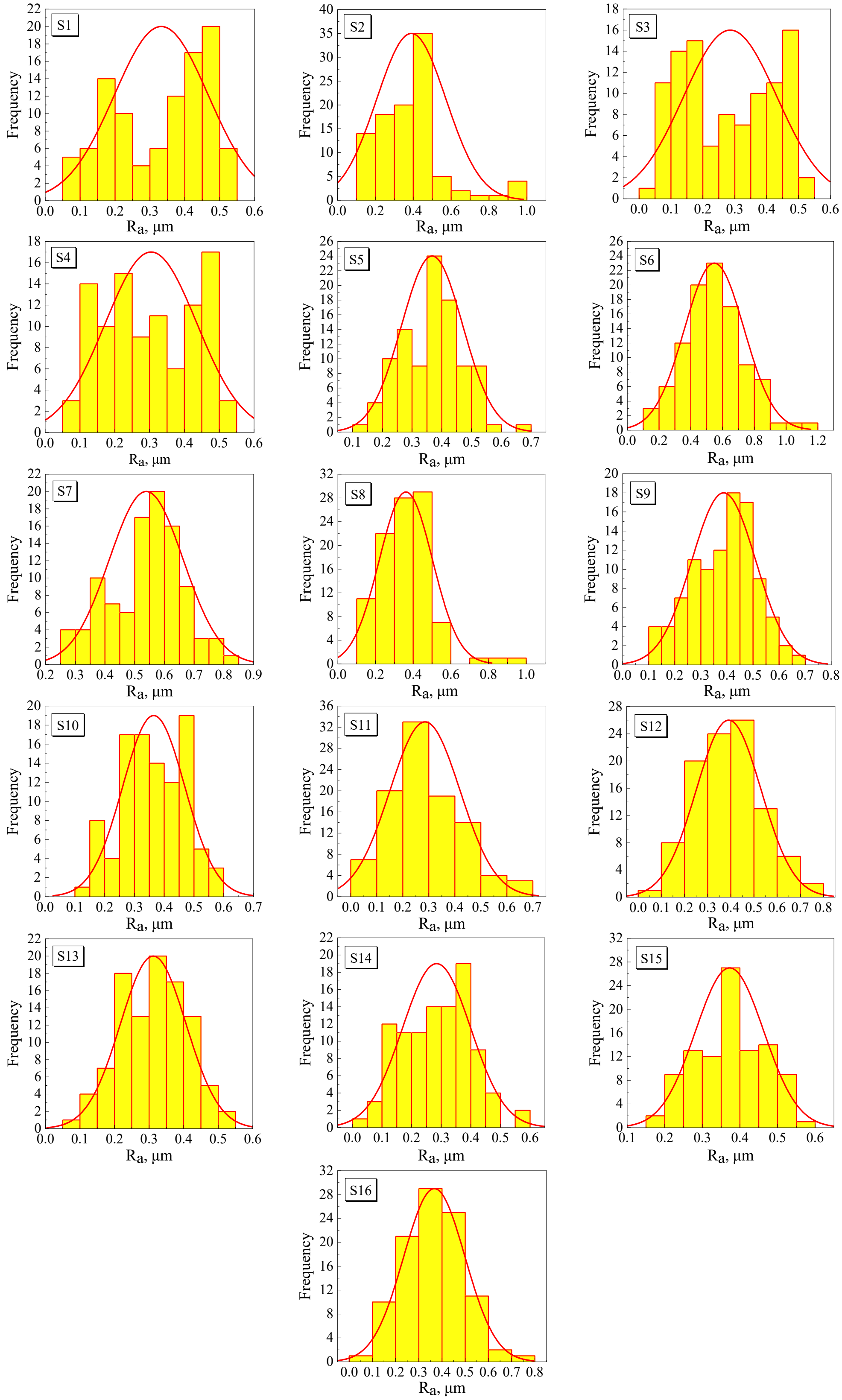

Fig. 31. Histograms of R_a values in each studied rock sample.

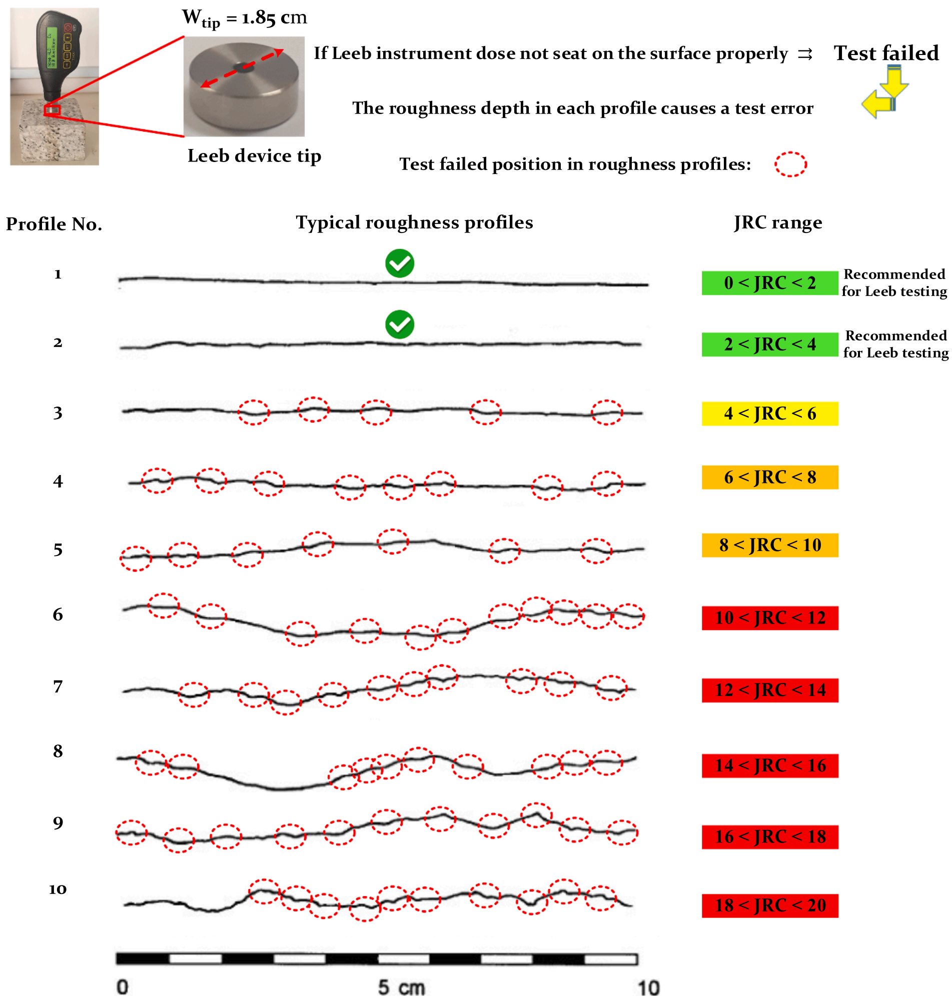

Fig. 32. Usability of the Leeb hardness test in different roughness classes.

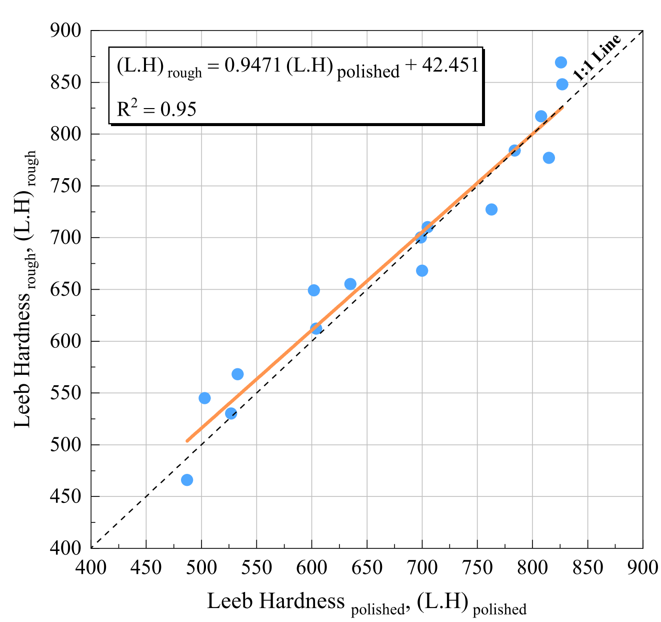

Fig. 33. Relationship between Leeb hardness of the rough and polished surface.

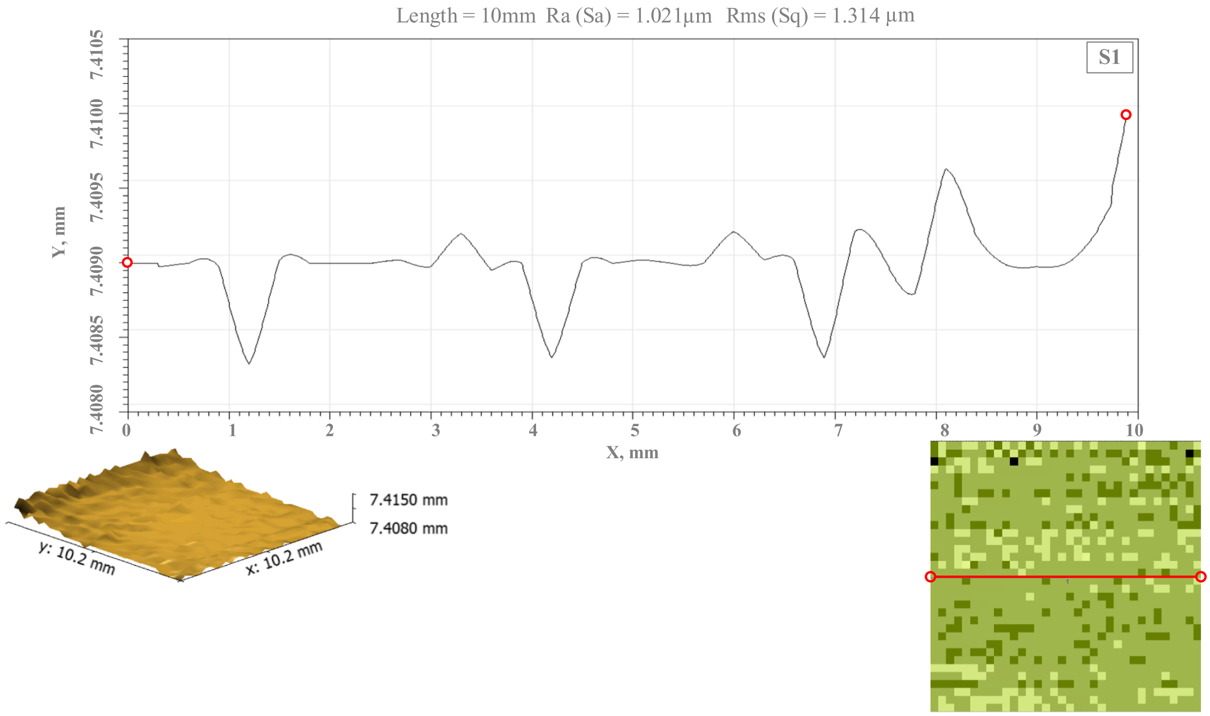

Fig. 34. Extracted profile from sample No. 1.

engineering. To achieve this goal, 33 rock samples have been used with various geological, mechanical, and physical properties. The application of the Leeb test in rough samples was also investigated on 16 different rock samples. The most important results obtained from the studies are as follows:

- As a first result, both block and core samples can be used to reliably measure the Leeb hardness. Based on the results, the proposed minimum dimension for determining the Leeb hardness in block samples is $10\times10\times5$ *cm* (or a volume of 500 cm^3).
- In core samples, both body and end surface modes can be used. The experimental results show that with the increase in L/D, the Leeb hardness increases non-linearly. On the other hand, no specific trend has been observed in some samples with $L/D < 1.6$. Therefore, the minimum L/D ratio for both modes was suggested as 1.6. This ratio corresponds to $V_{critical} \approx 198\ cm^3$.
- The statistical analyses show that the physical parameters, including density and porosity, have reasonable effects on the Leeb hardness.
- One of the most important parameters in measuring the Leeb dynamic hardness is the surface temperature of the samples. For this purpose, the samples were exposed to different temperatures, including −30, 0, 20, 50, 100, and 150 °*C*. The key point is to investigate the uniform distribution of temperature effects on the surface of the rock sample. For this purpose, a thermometer camera was used in this research to control temperature variations. The results showed that, with increasing the surface temperature of the samples, the Leeb dynamic hardness decreases slowly in both igneous and sedimentary samples. As a result, the surface temperature of the samples will cause variations in the Leeb hardness of sedimentary and igneous samples, albeit low.
- Additionally, based on the authors' experiences in performing the Leeb hardness tests, in samples with high porosity, there will be a lot of uncertainty in the results. In other words, when the indenter of the Leeb device is placed near the pores, the device gives an error. Therefore, it is recommended that the impact points of the samples be carefully selected to avoid possible errors.
- The results of roughness tests showed that the Leeb hardness of rough samples could be determined with high accuracy from the Leeb hardness of polished samples. This correlation was obtained with a coefficient of determination of 0.95, which indicates the high accuracy of the correlation.
- The usability of the Leeb hardness test in rock materials based on arithmetic roughness average values (R_a) using the laser profilometer was investigated. The Leeb hardness test was successfully applied to the rock samples with a $R_a < 2\ \mu m$, according to the data collected from 16 rock samples.
- A geometrical survey was also performed on 10 Bartons' roughness profiles. The results showed that the Leeb hardness test could be used effectively in classes 1 and 2, as well as locally in classes 3 to 10.

Finally, given its portability and precision, and consideration of the aforementioned requirements, the Leeb hardness test can be applied in the majority of rock engineering applications. Further studies could focus on the metamorphic rock types, such as conglomerate, phyllite, chlorite schist, and serpentinite to determine their anisotropy effects on the Leeb dynamic hardness test. Also, the roughness studies results can help to have an initial insight into the effect of surface roughness of rocks

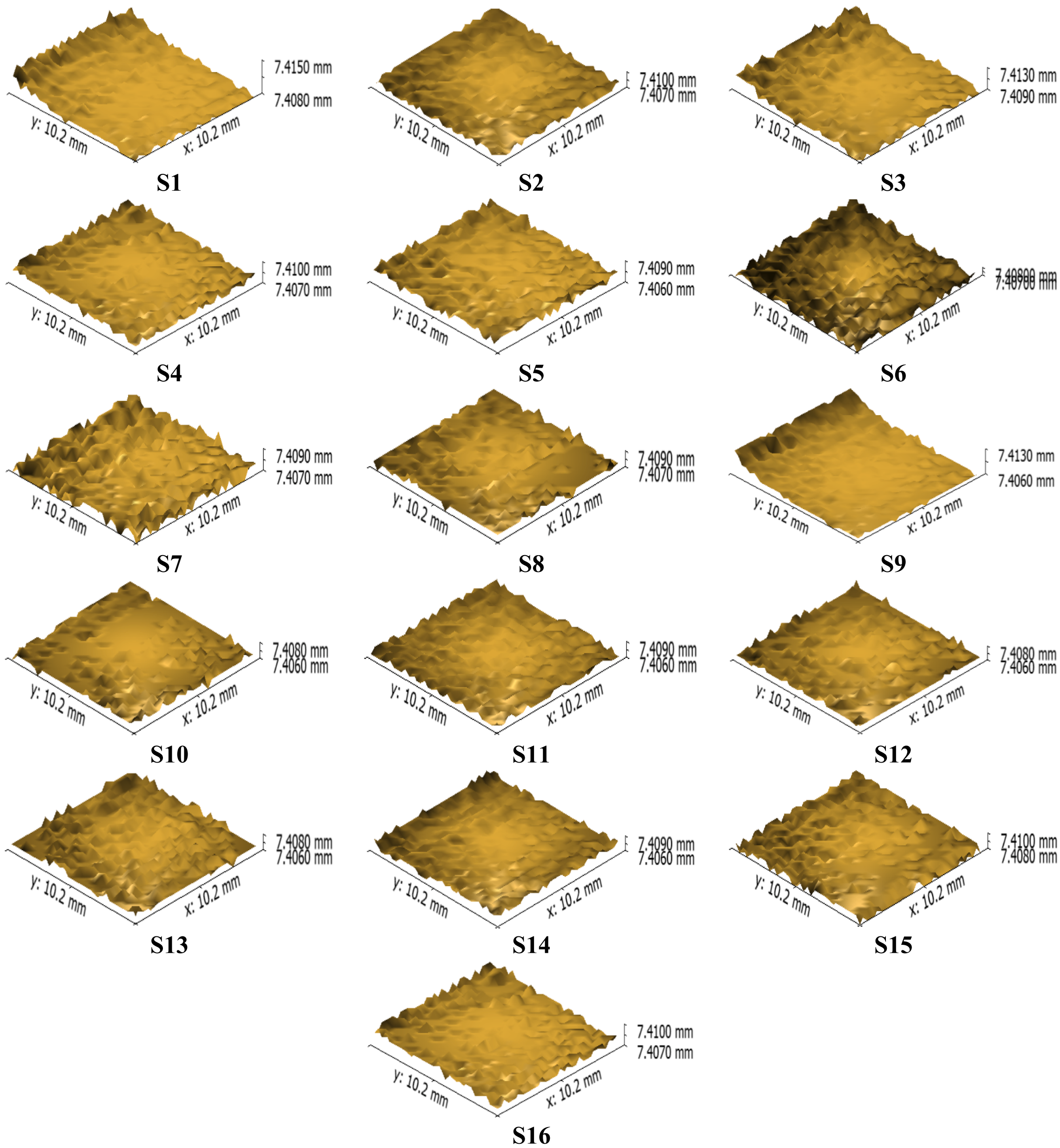

Fig. 35. 3D surface plots of all samples in 1×1 *cm* of surfaces.

Table 4
Results of the statistical analysis of measured R_a values of studied samples.

Sample No.	Rock name	Statistical parameters				
		Max	Min	Mean	Median	Std. Dev
S1	Tuff	0.513	0.064	0.332	0.364	0.134
S2	Limestone	0.980	0.111	0.389	0.391	0.182
S3	Limestone	0.500	0.049	0.286	0.276	0.145
S4	Rhyolite	0.503	0.096	0.304	0.294	0.131
S5	Limestone	0.668	0.140	0.367	0.380	0.102
S6	Limestone	1.119	0.148	0.547	0.537	0.186
S7	Limestone	0.804	0.259	0.539	0.562	0.124
S8	Marble	0.989	0.106	0.362	0.352	0.141
S9	Limestone	0.654	0.108	0.387	0.402	0.122
S10	Limestone	0.582	0.139	0.365	0.362	0.104
S11	Tuff	0.655	0.011	0.285	0.274	0.134
S12	Limestone	0.734	0.098	0.391	0.384	0.139
S13	Granodiorite	0.511	0.083	0.312	0.314	0.094
S14	Quartz monzonite	0.594	0.026	0.284	0.292	0.115
S15	Tuff	0.551	0.161	0.372	0.373	0.090

Table 5
Results of the statistical analysis of measured Leeb hardness values of polished and rough surfaces.

Sample No.	Rock name	Polished surface					Rough surface				
		Max	Min	Mean	Median	Std. Dev	Max	Min	Mean	Median	Std. Dev
S1	Tuff	872	689	815	832	49.4	869	614	777	811	72.2
S2	Limestone	792	726	763	766	17.9	793	601	727	754	63.6
S3	Limestone	645	223	503	536	110.1	687	391	545	554	72.3
S4	Rhyolite	888	733	827	824	40	897	763	848	847	32.6
S5	Limestone	716	680	699	699	8.5	789	674	714	710	32.2
S6	Limestone	643	285	533	555	99	687	415	568	584	83.6
S7	Limestone	722	668	705	706	12.2	733	675	710	712	15
S8	Marble	642	532	604	605	29.4	647	552	612	614	24.5
S9	Limestone	694	513	635	653	51.6	723	500	655	678	64.2
S10	Limestone	567	348	487	507	63	578	313	466	465	76.7
S11	Tuff	755	617	700	727	45.4	758	600	668	668	50.4
S12	Limestone	693	217	527	552	130.6	668	234	530	578	125.8
S13	Granodiorite	849	669	784	792	43.2	844	687	784	791	38.2
S14	Quartz monzonite	875	660	826	848	59.7	899	823	869	874	23.9
S15	Tuff	709	525	602	568	48.9	782	575	649	629	61.9
S16	Muscovite granite	878	689	808	804	42.3	894	763	817	827	41.3

Table 6
The standard testing environment of the Leeb hardness method.

Testing information	Recommended
The shape of the rock sample	✔ Block ✔ Core
Minimum sample size	Block: 10×10×5 *cm* (or 500 cm^3) Core: $L/D = 1.6 \approx 198\ cm^3$ (NX-diameter)
Surface temperature	Room temperature
Number of impacts	Block samples: 18 Core samples: 17
Surface roughness	Class 1 and 2 of Barton's roughness profiles in total Class 3 to 10 of Barton's roughness profiles locally
Specimen vibration	Anti-vibration pad
Porous rock sample	Avoid testing near the pores of the rock surface

on Leeb dynamic hardness tests and can be used in the preliminary study of relationships between them. Moreover, to better understand the effect of surface roughness on the Leeb hardness in different rock samples, more studies are needed using laser profilers with higher accuracy.

8. Recommended testing method

In summary, in performing the Leeb hardness test, it is necessary to consider the items mentioned in Table 4:Tables 5 and 6.

CRediT authorship contribution statement

Sasan Ghorbani: Data curation, Writing – original draft. **Seyed Hadi Hoseinie:** Conceptualization, Methodology. **Ebrahim Ghasemic:** Investigation, Supervision. **Taghi Sherizadeh:** Visualization, Writing – review & editing.

Declaration of Competing 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.

Data availability

The data that has been used is confidential.

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