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ORIGINAL PAPER

A new rock hardness classification system based on portable dynamic testing

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Abstract
Hardness is one of the critical physical characteristics of minerals and rocks, which indicates the resistance of the rock to penetration, scratch, or permanent deformation. As a basic concept, rock hardness has a significant role in rock mechanics and geological engineering and is an appropriate diagnostic tool for the classification of minerals and rocks. The main purpose of this study is to guide rock engineers to measure the rock hardness faster, easier, and more accurately using Leeb's dynamic hardness test. Accordingly, this paper presents a new rock hardness classification system based on the Leeb dynamic and portable hardness testing method. It is a well-known method for its fast and straightforward procedure testing equipment. A set of 33 different rock types were collected and tested during this study. Next, in-depth microscopic mineralogical studies were performed to determine the precise Mohs hardness value. The Mohs hardness was considered the leading hardness benchmark during the experimental studies, and the Leeb hardness was adopted to classify based on this hardness. A series of laboratory studies and statistical analysis was performed to predict the Shore and Vickers hardness using Leeb hardness. Finally, based on the comparative studies, it is recommended to classify the rocks considering the Leeb hardness method in six different categories: extremely soft (1–250), soft (250–450), moderately soft (450–750), moderately hard (750–850), hard (850–920), and extremely hard (920–1000). The provided classification could be useful in a vast range of rock engineering applications, especially for feasibility studies of rock engineering projects and engineering geology.

Keywords Leeb dynamic hardness · Mohs hardness · Vickers · Shore · Rock hardness classification system

Introduction

The science of classification is called taxonomy, which deals with theoretical aspects of classification, including its fundaments, principles, procedures, and rules. Classification is defined as the arrangement of objects into different groups based on their particular characteristics and relationships. This concept has played a vital role in engineering for centuries (Bieniawski 1989). Specifically, concerning rock engineering projects, classification is used for practical design, generally in feasibility studies (Goel and Singh 2011).

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The hardness concept is one of the most investigated properties of materials, and it is not easy to understand it correctly. Due to the complexity of hardness from the engineering perspective, a unique and comprehensive definition has not been recommended for hardness. However, many narrow-vision definitions of rock hardness have been presented by different researchers from the viewpoint of different applications and mechanisms. Mohs (1812) stated that hardness is the stability of a mineral that shows against the particle's displacement. Jimeno et al. (1995) believe that hardness is the first resistance that must be overcome during the rock excavation process. Based on Verhoef (1997), hardness refers to the resistance of a rock or mineral against a cutting tool. Nevertheless, generally, hardness indicates the rock's resistance to penetration, scratch, or permanent deformation (Heiniö 1999; Demirdag et al. 2009; Winkler 2013). In another view, hardness is the resistance of a material to the penetration of another hard material (Gokhale 2010).

From an application perspective, hardness is widely used in rock mechanics, geological engineering, and excavatability in civil and mining fields. This property is considered in vital classification systems such as rock mass drillability index (Hoseinie et al. 2008), rock penetrability index (Hoseinie et al. 2009), coal cuttability (Bilgin et al. 1992), excavatability including diggability, rippability, blastability (Karpuz 1990; Jimeno et al. 1995; Basarir and Karpuz 2004), abrasivity assessment (Yılmaz 2011), sawability (Kahraman and Gunaydin 2008), and also classification of mechanical properties (Aligholi et al. 2017). In these important classification systems presented by researchers, the hardness parameter has been introduced as one of the key parameters. Additionally, Vickers hardness of rocks (as one of the hardness methods with indentation mechanism) can be used to predict the cutter life in tunneling projects (Hassanpour 2018). The hardness is also applied in geomorphology and environmental field investigations (Aoki and Matsukura 2007; Viles et al. 2011; Alberti et al. 2013; Coombes et al. 2013; Mol 2014; Desarnaud et al. 2019).

In general, hardness affects the physical and mechanical characteristics and machinability properties of the rocks. Many researchers have described the relationships between physical, mechanical, thermal properties of the rocks and hardness (Bell and Lindsay 1999; Saotome et al. 2002; Shalabi et al. 2007; Freire-Lista et al. 2016; Sajid et al. 2016; Freire-Lista and Fort 2017; Çelik and Çobanoğlu 2019; Desarnaud et al. 2019; Ajalloeian et al. 2020; Aladejare 2020; Zhang et al. 2020; Gomez-Heras et al. 2020). This bilateral interaction between hardness and other rock parameters such as elastic dynamic properties (Ghorbani et al. 2022) indicates that hardness is a critical part of engineering judgment about rock, and it is crucial to study and explore properly. However, so far, no classification has been provided for the Leeb method that can be used to determine the degree of hardness of the rocks. Therefore, measurement procedures, classification, duration, and accuracy of the rock hardness testing methods and standards have been a challenge and a hot topic for rock and mineral engineers for many decades.

Many rock hardness testing methods have been developed and applied in several applications using different mechanisms and considering various rock characteristics. Rock hardness testing methods are classified into different types considering the tool-rock interaction mechanisms, including scratch, indentation, grinding, and rebound. Non-destructive dynamic hardness methods generally involve the Shore, Schmidt, and Leeb (or Equotip) methods.

Nondestructive techniques capable of measuring in situ surface hardness with lower impact energies are therefore of interest to researchers and engineers working in both the natural and built environment (Viles et al. 2011; Ulusay and Erguler 2012; Coombes et al. 2013). One of the non-destructive portable testing techniques (NDT) for measuring rock hardness is the Leeb dynamic hardness method. It has been increasingly applied in rock mechanics and geomorphological research in the recent decade.

The Leeb hardness test method has been introduced by Leeb (1978) and was initially developed for measuring the strength of metallic materials. This method was developed to offer a faster, more comfortable, and practical hardness test, which could be applied in different test directions with a wider hardness scale (Kompatscher 2004). The theoretical basis of the Leeb hardness method is based on the dynamic impact principle: the rebound velocity ($V_{Rebound}$) of an impact body with a 3 mm diameter tungsten carbide spherical tip on a material's surface is recorded and reported relative to its downward, or impact velocity (V_{Impact}) (Corkum et al. 2018).

The Shore and Schmidt hammer hardness methods have performance limitations despite some advantages. The Equotip has much lower impact energy than the Schmidt hammer (L-type impact energy 735 Nmm and N-type 2207 Nmm). Having low impact energy gives the Equotip advantages over the Schmidt hammer, especially on weathered and weak rocks (Desarnaud et al. 2019). In practical applications, the Shore and Schmidt instruments have some limitations. The Shore hardness is, essentially, a bench-top laboratory tool that is not convenient for field applications (Çelik and Çobanoğlu 2019). Although the Schmidt hammer can be used in both the field and the laboratory, due to its high impact energy, it is not appropriate for the testing of weak or friable rock materials (Aydin and Basu 2005; Aoki and Matsukura 2007; Yilmaz 2013). Another disadvantage of the Schmidt method used by geologists is that it has some practical errors (test condition and hammer calibration) (Aoki and Matsukura 2007; Hoseinie et al. 2009). Since the Leeb device system is electronic, it produces fewer errors than the Schmidt device, which is mechanical. For these reasons, in rock engineering and geological aspects, the Leeb method is a good alternative for them. Therefore, the current paper aims to study the Leeb non-destructive dynamic hardness method and its interaction with the other hardness scales in detail. As the main goal, it has been attempted to develop a new rock hardness classification system based on the Leeb method as a portable and fast hardness testing method. In other words, according to the presented classification based on the Leeb portable test, it is possible to quickly and easily determine the rock hardness class.

Materials and methods

To develop a new classification system for rock hardness assessment, we have to provide and study many different rock types. It enables us to explore the different perspectives of the hardness measurements and associated dominant factors. Thus, a set of 33 different rock types with various

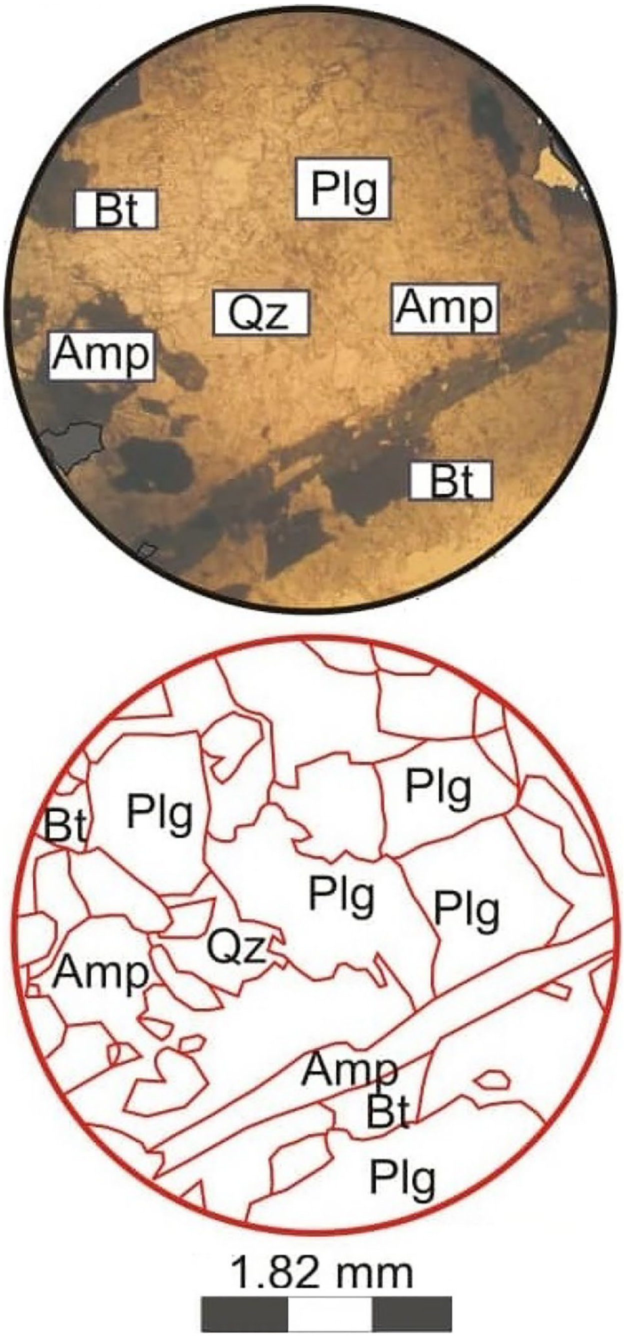

Fig. 1 Sample (S23: dacite) of scaled mineralogical composition analysis using crossed polarized light (XPL)

origins are collected and prepared for experimental studies. These rock samples were selected due to their different mineralogical, physical, and mechanical properties, especially for their hardness characteristics.

In the first stage of the studies, fresh boulder samples were selected from different mines and quarries, mostly ornamental stone quarries, and transferred to the laboratory. These boulders were cut and prepared in suitable sizes for Leeb, Shore, and Vickers tests, and two thin sections were prepared from each rock sample for mineralogical studies and to determine the Mohs hardness. Finally, the sides of the specimens were made flat, smoothed, and polished.

Mineralogical studies

Since most minerals are anisotropic and might exhibit different hardness values when scratched in different directions, thin sections were prepared and analyzed in two directions perpendicular to each other. By applying this method, each mineral's exact contribution to the rock formation and the mineralogical composition of each rock type was determined and recorded correctly. The mineralogical description of rocks was obtained from thin section images taken by a camera mounted on a polarizing microscope. An Olympus polarization microscope (BH2 series) with crossed polarized light (XPL) was applied in the studies (Fig. 1). Figure 2 presents microphotographs taken from thin sections of each rock type. The studied rocks' microscopic properties are also very variable in addition to the rocks' physical and mechanical properties. Petrographic characteristics of rocks such as grain size, grain shape, and mineralogical composition significantly affect the physical and mechanical properties (Hoseinie et al. 2019). The studied rocks contain three groups of fine-grained, medium-grained, and coarse-grained fabrication. For example, as shown in Fig. 2, the diorite (No. 28) and tuff samples (No. 27) are coarse-grained and fine-grained rocks, respectively.

As shown in Table 1, the studied rock types include a vast range of minerals, and the different mineralogical compositions enable the researchers to cover a wide range of hardness. As shown in this table, the igneous samples' dominant minerals are quartz, plagioclase, K-feldspar, amphibole, and biotite. In the sedimentary samples, there are mostly three minerals, sparite calcite, micrite calcite, and hematite.

Hardness measurement experiments

Mohs hardness scale

Mohs scale is one of the most famous and widely used methods for measuring rock hardness due to its relationship to rocks' mineralogical characteristics. According to this method's microscopic nature, the Mohs scale has acceptable accuracy in determining rocks' hardness. This scale is also the most popular and applicable method for evaluating and classifying rock hardness because it is directly based on mineralogical studies (Hoseinie et al. 2009, 2012). Therefore, in this study, the Mohs method has been used as the benchmark for studied rock types' hardness. When considering the Mohs hardness of every contained mineral (H_i) and its frequency in rock composition (A_i%), the average hardness of each thin section of rock can be calculated by Eq. 1. Finally, the calculated average hardness is considered to be the Mohs hardness of the rock. Table 2 shows the calculated average Mohs hardness values for studied rock types. As an example, Fig. 3 shows how the mean Mohs hardness for sample No.22 is calculated.

$$\text{Mean Mohs hardness} = \sum_{i=1}^{n} A_i \times H_i \tag{1}$$

Leeb dynamic hardness

In the Leeb instrument, an impact body made by the diamond or tungsten carbide is shut vertically to the specimen's surface. Next, the electronic indicator measures the impact and rebound velocities. The mentioned velocities are measured with a permanently mounted magnet, which moves through a coil in an impact device and induces an electric voltage on both the impact and rebound movements. Finally, the Leeb hardness number is calculated by dividing the rebound velocity by the impact velocity as given in Eq. 2 (ASTM A956-06 2006).

$$\text{L.H} = \frac{\text{Rebound velocity}}{\text{Impact velocity}} \times 1000 \tag{2}$$

Different types of impact bodies with different energy levels are available for Leeb hardness testing (Çelik and Çobanoğlu 2019). Mainly, six types of impact devices are applied including D, DC, E, D + 15, G, and C (ASTM A956-06 2006). In general, the D-type impact body is commonly used. The impact energy of the D-type Leeb tester is 11Nmm which is equal to almost 1/200 of the N-type Schmidt hammer's energy, and 1/66 of the L-type Schmidt hammer (Moses et al. 2014). Also, the impact energies of C and G types are 3 Nmm and 90 Nmm, respectively (Verwaal and Mulder 1993). Due to low-energy impact testing, the Leeb hardness testing is much more suitable for measuring the rock hardness in comparison with the higher-energy Schmidt hammer test, especially in weak and weathered rock surfaces (Corkum et al. 2018).

Since the size of the block samples is so effective in Leeb hardness testing results, at the first stage, the optimum size of the samples was investigated. As seen in Fig. 4, in cubic samples with a higher thickness of 5 cm, the test results are independent of the sample thickness, Leeb hardness is constant. Therefore, all hardness testings were carried out on 10 × 10 × 5 cm (or a volume of 500 cm^3) blocks. Seventeen single impacts were performed on each sample, and the average of these impact numbers was assigned as the Leeb hardness value of each sample. The tests were performed by the ITI-130 model instrument shown in Fig. 5. The results of the Leeb hardness tests are presented in Table 2.

So far, no standard (ISRM, ASTM, etc.) has been provided to determine the Leeb test on rock samples. There is still no well-established testing procedure for using the Leeb dynamic hardness test in rock mechanics. Thus, in this paper, a testing pattern has been used according to Fig. 6 to measure the Leeb hardness of rock samples. The main point in performing the Leeb test is that the impact points must cover the entire surface of the sample. In the suggested pattern, 1 cm of each side of the sample block is not considered to minimize the effect of micro-cracks caused by rock cutting in the sample preparation process. Finally, the average of 17 tests on the sample surface was reported as the Leeb dynamic hardness of each rock.

Moreover, for minimizing the uncertainty, during the Leeb tests, three sides of the sample blocks were tested and there was not any significant difference among the hardness values. Therefore, it was concluded that the Leeb hardness scale is independent of the direction. According to Çelik and Çobanoğlu (2019), unlike the classic Schmidt hardness, the rebound values acquired by the Leeb hardness are independent of impact direction, which eliminates the need to use impact direction conversion curves.

Shore hardness

Shore hardness is a well-known convenient and non-destructive rock hardness testing method and is widely used in rock engineering (Altindag and Güney 2006). This device is presented in two models: C and D. The Shore hardness tester is a relatively inexpensive and compact instrument, and its simplicity of operation permits many readings in a short time (Winkler 2013). In this research, to perform a Shore hardness test on the samples, the Agg-EQ-200 Shore D hardness tester is applied, as shown in Fig. 7.

The test procedures and sample preparation were carried out based on Holmgeirsdottir and Thomas (1998) recommendations. They concluded that model D is read more easily than model C and it is also applicable to small test specimens such as rock aggregates or samples which are too small for most of the other kinds of index testing (Holmgeirsdottir and Thomas 1998). They also found that the D-type Shore hardness is independent of the sample dimension, and at least 30 impacts are required to test on each sample. The Shore hardness test is also performed on the same rock sample with dimensions of 10 × 10 × 5 cm, and their average was reported as the Shore hardness of each rock type. Results of the Shore hardness tests are also presented in Table 2.

Vickers hardness

Vickers is an indentation hardness testing method that determines a material's hardness based on the strength against a square-based pyramidal diamond's penetration. It was

Fig. 2 Typical microphotographs from thin sections of each studied rock type

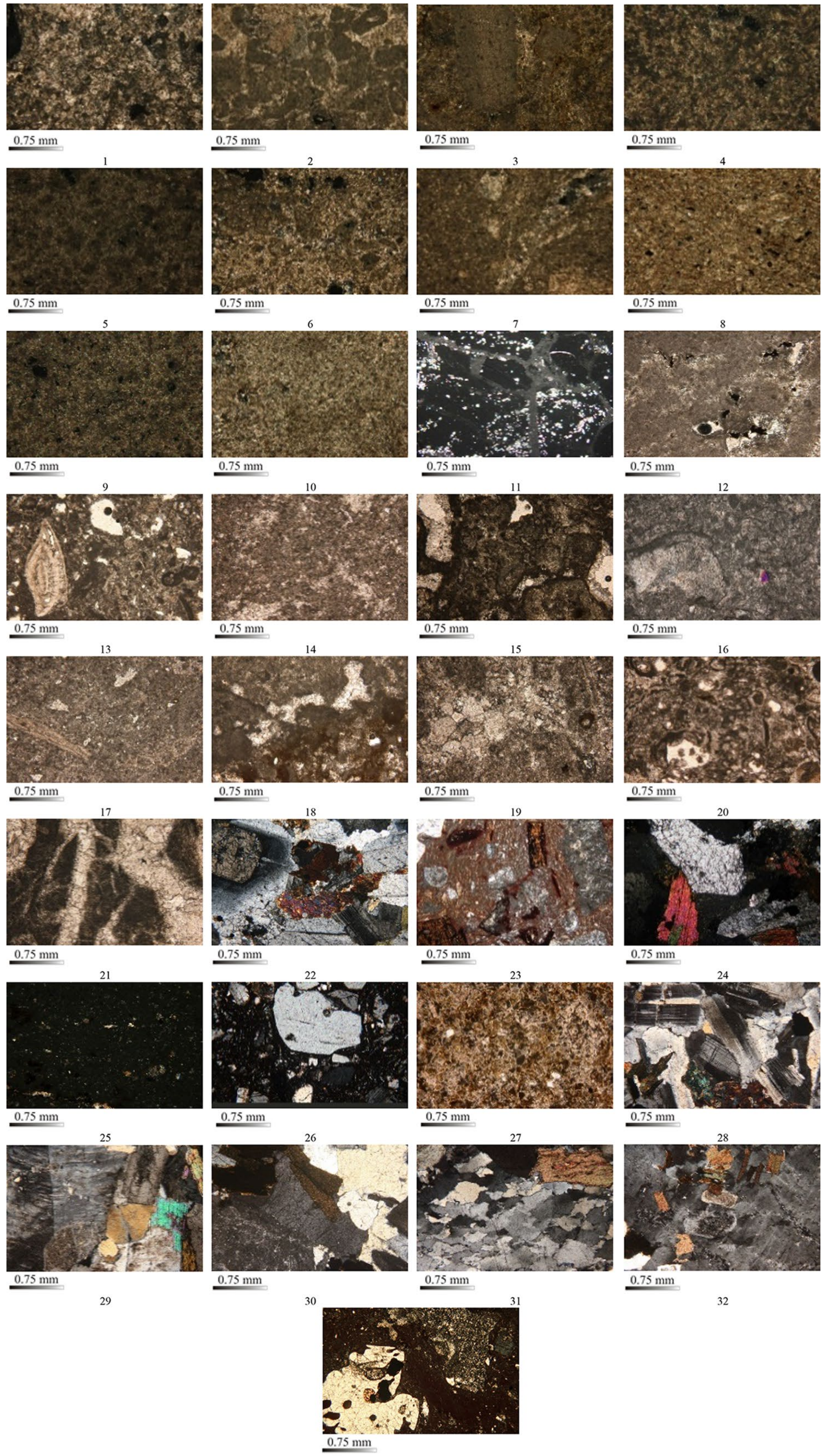

Table 1 Results from mineralogical and petrographic analysis of thin sections of studied rock samples

Sample no	Rock name	Percentage of mineral (%)													
		Sparite calcite	Micrite calcite	Hematite/ Magnetite	Coral parts	Quartz/clay	Plagioclase	K-feldspar	Amphibole	Biotite	Pyroxene	Muscovite	Opaque minerals	Halite	Other
S1	Limestone	100	-	-	-	-	-	-	-	-	-	-	-	-	-
S2	Fossiliferous limestone	23	52	5	20	-	-	-	-	-	-	-	-	-	-
S3	Fossiliferous limestone	25	50	5	20	-	-	-	-	-	-	-	-	-	-
S4	Limestone	28	72	-	-	-	-	-	-	-	-	-	-	-	-
S5	Limestone	15	75	-	10	-	-	-	-	-	-	-	-	-	-
S6	Limestone	45	40	5	7	3	-	-	-	-	-	-	-	-	-
S7	Limestone	48	45	7	-	-	-	-	-	-	-	-	-	-	-
S8	Limestone	90	4	-	-	Q = 3 C = 3	-	-	-	-	-	-	-	-	-
S9	Dolomitic limestone	60	40	-	-	-	-	-	-	-	-	-	-	-	-
S10	Limestone	52	38	10	-	-	-	-	-	-	-	-	-	-	-
S11	Salt	-	-	-	-	-	-	-	-	-	-	-	-	100	-
S12	Cavernous limestone	45	50	M = 5	-	-	-	-	-	-	-	-	-	-	-
S13	Limestone	55	30	-	15	-	-	-	-	-	-	-	-	-	-
S14	Limestone	20	75	-	5	-	-	-	-	-	-	-	-	-	-
S15	Cavernous limestone	48	46	4	-	2	-	-	-	-	-	-	-	-	-
S16	Limestone	45	40	2	5	8	-	-	-	-	-	-	-	-	-
S17	Cavernous limestone	37	57	6	-	-	-	-	-	-	-	-	-	-	-
S18	Travertine	38	49	13	-	-	-	-	-	-	-	-	-	-	-
S19	Cavernous limestone	66	29	3	-	2	-	-	-	-	-	-	-	-	-
S20	Limestone	47	48	5	-	-	-	-	-	-	-	-	-	-	-
S21	Limestone	48	47	3	-	2	-	-	-	-	-	-	-	-	-
S22	Granodiorite	-	-	-	-	6	55	-	20	12	5	-	2	-	-
S23	Dacite	-	-	-	-	20	42	-	15	20	-	-	3	-	-
S24	Quartz monzonite	-	-	-	-	11	33	41	5	8	-	-	2	-	-
S25	Tuff	20	-	-	-	5	30	-	-	-	-	-	-	-	45*
S26	Rhyolite	-	-	-	-	47	34	5	-	12	-	-	2	-	-
S27	Tuff	10	-	-	-	Q:5 C:25	10	-	-	-	15	-	5	-	30**

Table 1 (continued)

Sample no	Rock name	Percentage of mineral (%)													
		Sparite calcite	Micrite calcite	Hematite/ Magnetite	Coral parts	Quartz/clay	Plagioclase	K-feldspar	Amphibole	Biotite	Pyroxene	Muscovite	Opaque minerals	Halite	Other
S28	Diorite	-	-	-	-	10	45	-	25	12	5	-	3	-	-
S29	Muscovite granite	-	-	-	-	30	15	40	-	3	-	11	1	-	-
S30	Granite	-	-	-	-	21	25	30	8	15	-	-	1	-	-
S31	Mylonite granite	-	-	-	-	25	15	48	-	10	-	-	2	-	-
S32	Sino-granite	-	-	-	-	12	28	44	-	12	-	-	-	-	4**
S33	Tuff	10	-	-	-	20	15	5	2	3	-	-	-	-	45**

*Chlorite and clay minerals, **iron oxide and fine-grained minerals

Table 2 Results of hardness testing experiments

Sample no	Rock name	Rock hardness values			
		Mohs	Shore	Vickers	Leeb
S1	Limestone	3	86.6	100.6	524
S2	Fossiliferous limestone	3.24	82	121.7	699
S3	Fossiliferous limestone	3.24	87.4	150	702
S4	Limestone	3	85.1	102	554
S5	Limestone	3.05	79.4	135.3	580
S6	Limestone	3.29	69.5	104.7	533
S7	Limestone	3.19	79.5	130	705
S8	Limestone	3.83	84.2	181.3	763
S9	Dolomitic limestone	3	80.1	121.7	568
S10	Limestone	3.08	76	81.8	503
S11	Salt	2.25	41	68	289
S12	Cavernous limestone	3.14	82.9	79.6	542
S13	Limestone	3.08	80.8	96.6	635
S14	Limestone	3.03	79.4	86.6	591
S15	Cavernous limestone	3.19	83.1	73	570
S16	Limestone	3.4	85.8	123.9	676
S17	Cavernous limestone	3.1	73	70.4	487
S18	Travertine	3.36	87.1	82.7	580
S19	Cavernous limestone	3.16	81.4	79.7	527
S20	Limestone	2.9	70	72	459
S21	Limestone	3.16	79.5	87.7	556
S22	Granodiorite	5.67	90.9	122	784
S23	Dacite	5.58	99	312.3	853
S24	Quartz monzonite	5.91	93.9	217	826
S25	Tuff	4.47	82.5	92	700
S26	Rhyolite	6.17	95.9	305.8	873
S27	Tuff	4.5	78.1	85.6	602
S28	Diorite	5.5	86	245	825
S29	Muscovite granite	5.86	92.6	112.5	808
S30	Granite	5.75	90.9	174.7	830
S31	Mylonite granite	5.96	94.9	293.7	872
S32	Sino-granite	5.77	92.2	281.7	816
S33	Tuff	5.49	91	158.7	815

initially introduced by Smith and Sandly (1922). To measure the Vickers hardness, an average of three to five tests is assigned as the value of micro-hardness of rock-forming minerals (Xie and Tamaki 2007; Aydin et al. 2013).

In this study, the same blocks used in previous tests by the dimensions of 10 × 10 × 5 cm were tested by an advanced universal hardness testing machine, KB Prüftechnik (Fig. 8). This device was equipped with a USB camera, high load stage range, and associated KB HardWin XL software package.

Considering the laboratory observations during the Vickers tests, and as it was reported by other researchers (Xie and Tamaki 2007), it was founded that the indentation area is not identified in some hard rock samples, as shown in

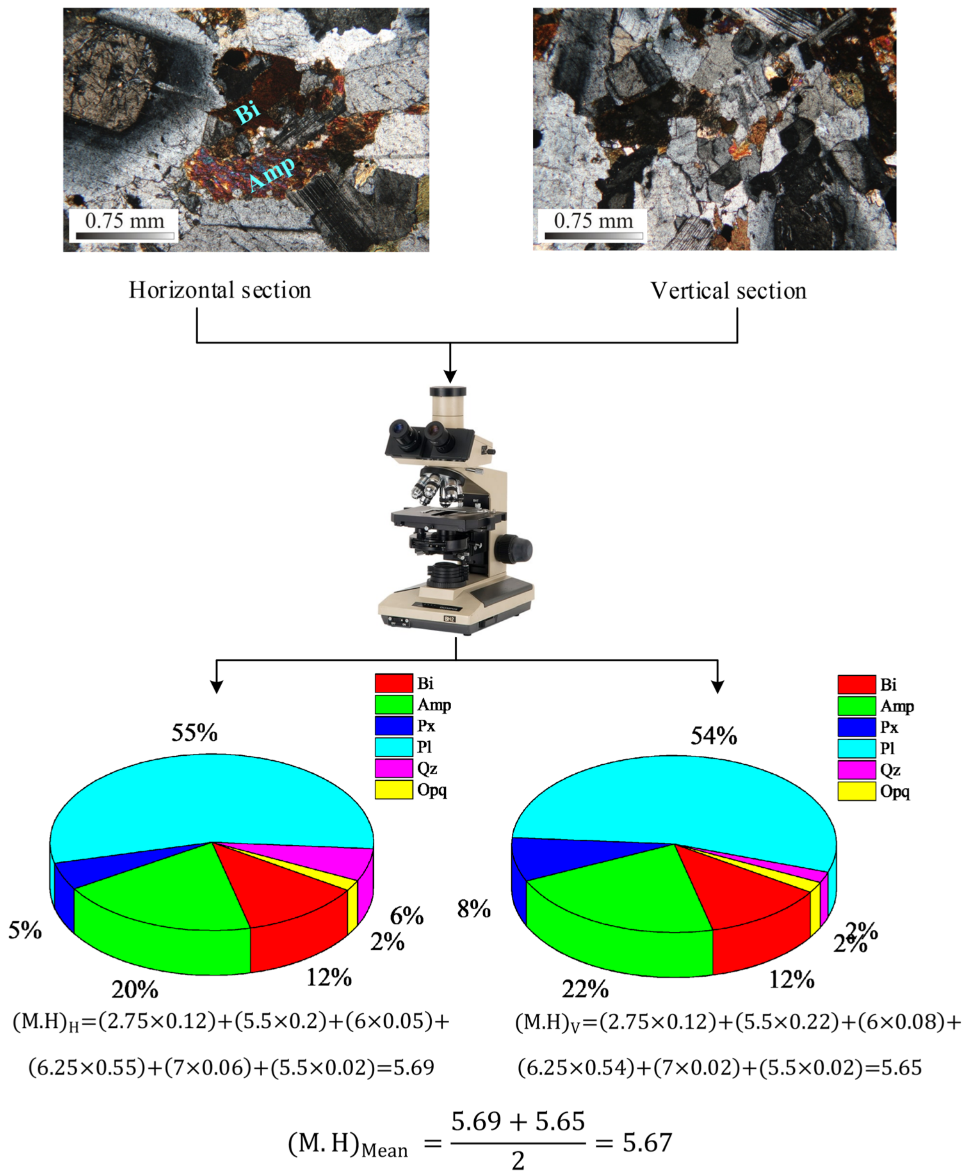

Fig. 3 Steps to calculate the mean Mohs hardness of sample No. 22

Fig. 8. Due to this problem, in some samples, several tests on different points of rock surfaces were carried out, and the average of the three precise tests was recorded as the Vickers hardness value. All tests were run at a load level of 50 Kg*f* (HV50). The results of the Vickers hardness tests are presented in Table 2.

Statistical analyses

After performing Vickers, Shore, Mohs, and Leeb hardness tests, the relationships between these methods have been investigated to identify any possible strong interactions and correlations among them. Since the Leeb hardness is the fastest and most portable method, the regression analysis focused on predicting the other hardness scales using the Leeb number. In the first stage, a statistical analysis was performed on collected data (presented in Table 2) to clarify the available data and probability density of different hardness classes. As shown in histograms of Fig. 9, all the measured rock hardness scales vary in an acceptable level of difference in hardness classes and potentially provide significant scientific background for further analyses. It is essential to mention that due to the difficulty of assessing very soft and very hard rock types, most of the samples used in this study are in the soft to hard classes (based on the Mohs classification).

After the statistical analysis, linear and nonlinear regression analyses were carried out on the collected laboratory data using the IBM SPSS statistical software version 22.0 (SPSS Inc.) at a 95% confidence level. Twenty-four statistical models were built to identify the best relationships between Leeb's dynamic hardness with Mohs, Shore, and

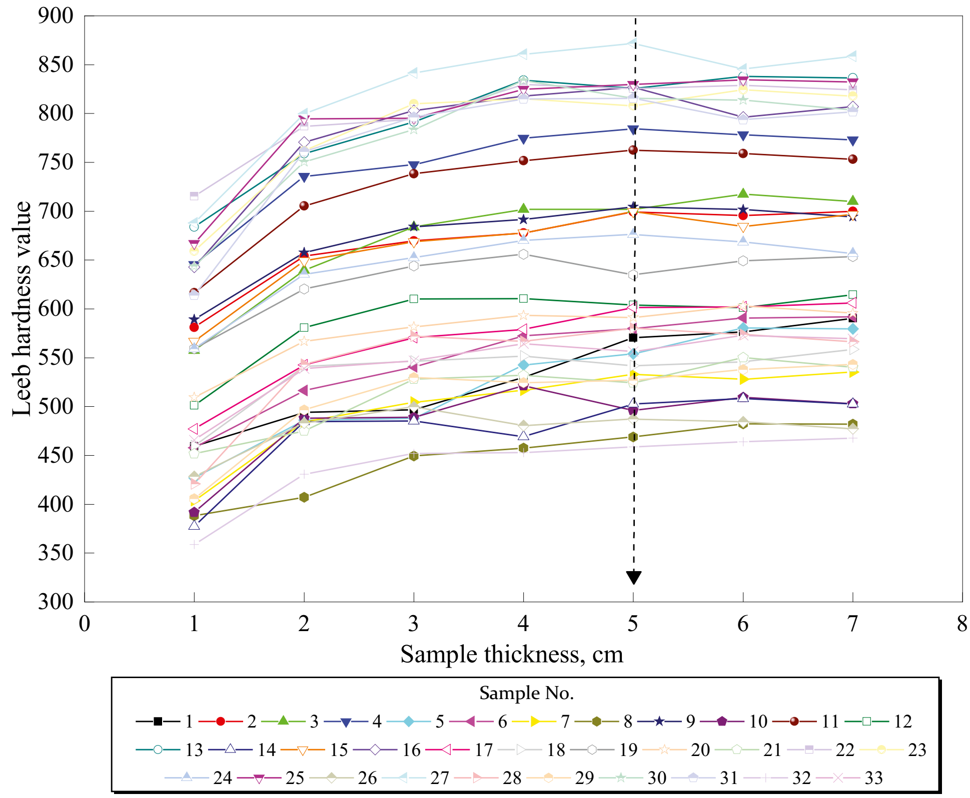

Fig. 4 The effect of sample thickness on Leeb hardness testing results

Vickers hardness methods in sedimentary and igneous rock samples separately.

In general, the best equations are selected based on two criteria: (a) the highest coefficient of determination (R^2) (or the highest coefficient of correlation, R) (b) the lowest standard error of the estimate (SEE).

The degree of fit to a curve can be measured by the value of the R^2, which measures the proportion of variation in the dependent variable, and the SEE, which is an important measure for indicating how close the measured data points fall to the estimated values on the regression curve. Logically, the relation with the highest R^2 is equivalent to the smallest SEE. In other words, better relation has a higher R^2 and a smaller SEE value (Jamshidi et al. 2018). Additionally, the significance values of the F statistic (Sig. of F) are less than 0.05, which means that the variation explained with a model is not due to chance. F statistic which is known as F value is suitable for comparison between two regression models. The larger value of F indicates a better relationship than other relationships which have a lower F value (Kamani and Ajalloeian 2019).

Therefore, considering the four functions of linear ($y = ax + b$), logarithmic ($y = a + bLn\ x$), power ($y=ax^b$), exponential ($y=ae^x$) and extracting the R^2, R, F value, Sig. level, and SEE for each regression equation, the best regression equations between Leeb hardness and other hardness methods have been selected. Tables 3 and 4 show all the statistical results of the regression analyses in sedimentary and igneous samples, respectively.

The equation of the best-fit line and coefficient of determination (R^2) are presented in Figs. 10, 11, and 12. As shown in Fig. 10, rock samples with a Mohs hardness greater than seven and smaller than two are absent in the studies. It is logically acceptable, as most rocks in engineering applications have a Mohs hardness within the range of two to seven. In contrast, rock types outside of this range are generally rare. It is shown that by increasing the Leeb hardness, the Mohs hardness of the rocks is increased power and exponentially by the coefficient of determination (R^2) equal to 0.75 and 0.82 in sedimentary and igneous rock samples, respectively. The SEE values for the presented equations in igneous and sedimentary rocks are 0.046 and 0.049, respectively. These measures show that the presented equations can be accepted as a reliable estimate for the Mohs hardness from Leeb dynamic hardness.

As can be seen in Fig. 10, there are two main clusters in the regression data, which refers to the difference between test nature and the range of hardness scales in Leeb and Mohs methods. The Leeb hardness varies from one to 1000, and the Mohs scale varies from one to 10; therefore, vast ranges from the Leeb point of view are scattered in a very narrow range in the Mohs scale. It could be seen in samples with Leeb hardness values of 450 to 850.

Figure 11 presents the correlations between Leeb and Shore hardness scales. As shown in this figure, by increasing the Leeb hardness, the Shore hardness is also increased with the power and exponential functions in sedimentary and igneous rock samples, respectively. There is a coefficient of determination equal to 0.82 between them in igneous rocks and it is 0.70 in sedimentary rock samples. Also, according to the results of statistical analyses, the SEE values of obtained regression equations for igneous and sedimentary samples are equal to 0.030 and 0.091, respectively, which indicate the reliable estimate for these equations.

In this plot, the experimental data distribution is much more continuous and homogenous, especially in the rock types with the Leeb hardness of more than 450. It confirms the similar nature of the tests (both of which are impact-based hardness testing methods). The broader range of scale causes the mentioned homogeneity of the experiment data.

The correlation between Leeb and Vickers hardness is presented in Fig. 12. Similar to other plots, by increasing the Leeb hardness, the Vickers hardness increases in both sedimentary and igneous rock samples. The best-fitted equations are exponential by the coefficient of determination equal to 0.68 and 0.64 in igneous and sedimentary rock samples, respectively. As shown in plots 10 to 12, the Leeb dynamic hardness test correlations with other hardness scales in igneous rock samples are more reasonable than in sedimentary rock samples.

In total, it is found that considering different ranges and different logics and mechanisms behind each studied rock hardness testing method; various testing methods can be correlated with the fast, portable and cheap hardness testing method, Leeb. Accordingly, due to the high coefficient of determination in regression analyses, it could be significantly applicable as a quick and initial assessment. For more accurate and reliable applications, a new classification system based on this method is developed, which could reduce the uncertainty and increase the reliability of this hardness method. In the following part, this concept is focused on and analyzed in detail.

Fig. 5 Leeb hardness instrument applied in the experiments

Classification of rock hardness methods using Leeb method

Beyond the technical and statistical interaction between the tested rock hardness methods and Leeb hardness, it is essential to determine the mentioned methods' exchange pattern. The main question is, what is the meaning of different numbers of the hardness scales? How can we judge rock hardness using a fast and reliable method?

In this paper, the scatter diagram technique is applied to develop a hardness classification of rocks based on the interaction between the Leeb method and Mohs hardness scale. For this purpose, it was necessary to determine the relationship between the Mohs scale reference minerals and Leeb hardness. Mohs hardness scale compares a mineral's

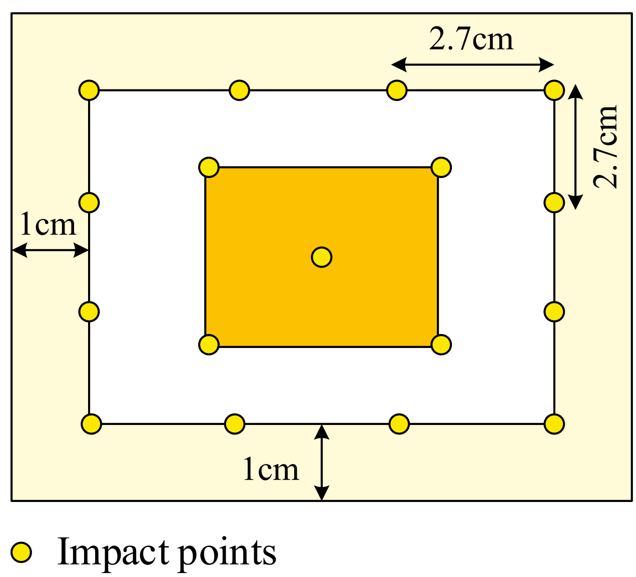

Fig. 6 Schematic view of performed testing pattern on rock block samples

Fig. 7 Applied D-type Shore hardness testing instrument

resistance to being scratched by ten reference minerals known as the Mohs hardness scales. The reference hardness is assigned to talc, gypsum, calcite, fluorite, apatite, feldspar, quartz, topaz, corundum, and diamond from one to ten, respectively. In other words, the main purpose is to establish the relationship between Leeb hardness and Mohs hardness of some main minerals first, and then further assess the proposed classification system. Therefore, initially, the regression analysis was carried out on the seven most common main minerals of the Mohs hardness (talc to quartz) scale with corresponding Leeb hardness. Since finding the big samples (laboratory testing scale) of the extremely hard minerals (topaz, corundum, and diamond) is impossible, the analysis was limited to a hardness value of one to seven. As can be seen in Fig. 13, as the Mohs hardness of the main minerals increases, the Leeb hardness increases with the power function, which shows significant relation based on the regression coefficient (R^2). In the next step, all available data from pairs Mohs-Leeb scales were scattered in the diagram as shown in Fig. 14. As shown in this figure, there is no data for the extremely soft and extremely hard classes because of the scarcity of such rocks in ordinary mining and construction projects.

Considering Fig. 14, as a critical and core part of this research, the Leeb hardness is divided into six classes based on the comparison with the Mohs method's microscopic analysis. In other words, based on the obtained laboratory data, and considering overlap area with Mohs hardness, the Leeb hardness classes are recommended as follows: $1 < \mathrm{L.H} < 250$, $250 < \mathrm{L.H} < 450$, $450 < \mathrm{L.H} < 750$, $750 < \mathrm{L.H} < 850$, $850 < \mathrm{L.H} < 920$, and $920 < \mathrm{L.H} < 1000$. In this classification, the numerical ranges for higher hardness classes are more limited due to these kinds of rocks' infrequency in nature and engineering projects. Based on pattern recognition and comparative analysis, the new proposed hardness system is developed and presented in Fig. 15.

As can be seen in Fig. 15, the six Mohs scale classes are 1–2, 2–3, 3–4.5, 4.5–6, 6–7, and 7–10. According to the Mohs classification, in the first two classes (ES and S), the numerical intervals are equal to one. In the third and fourth classes (MS and MH), the numerical intervals are equal to 1.5, but the difference for hard class (6–7) and extremely hard class (7–10) is equal to one and three, respectively. Additionally, it is observed that the obtained intervals for moderately soft class and moderately hard class in both Leeb hardness classification ($450 < \mathrm{L.H} < 850$) and Mohs classification ($3 < \mathrm{M.H} < 6$) are very important, because most of the studied rock samples in rock engineering researches are in MS and MH classes. In other words, the frequency of rock samples in these two classes is more than the other classes of the presented classification system. It should be noted that the numerical intervals of the six proposed classes do not need to have equal intervals according to the Leeb method. As in the Mohs classification, the intervals between the six classes are not equal.

The sensitivity of hardness to soft samples (Mohs hardness < 4.5) is higher than hard samples. This result has also been observed in studies related to the drillability of rocks that the sensitivity of drilling rate in soft rocks is higher than hard rocks. Therefore, in soft rocks, hardness study and exact recognition of hardness may be much more necessary than hard rocks (Hoseinie et al. 2012). Given the different numerical intervals of the Mohs classification, the intervals in the presented classification system presented in this paper also seem reasonable.

The most important advantage of the new classification system presented in this study is the quick determination of

Fig. 8 Applied universal hardness testing machine and indentation analysis: **a** not a clear area in a rock sample, **b** clear area in metal sample

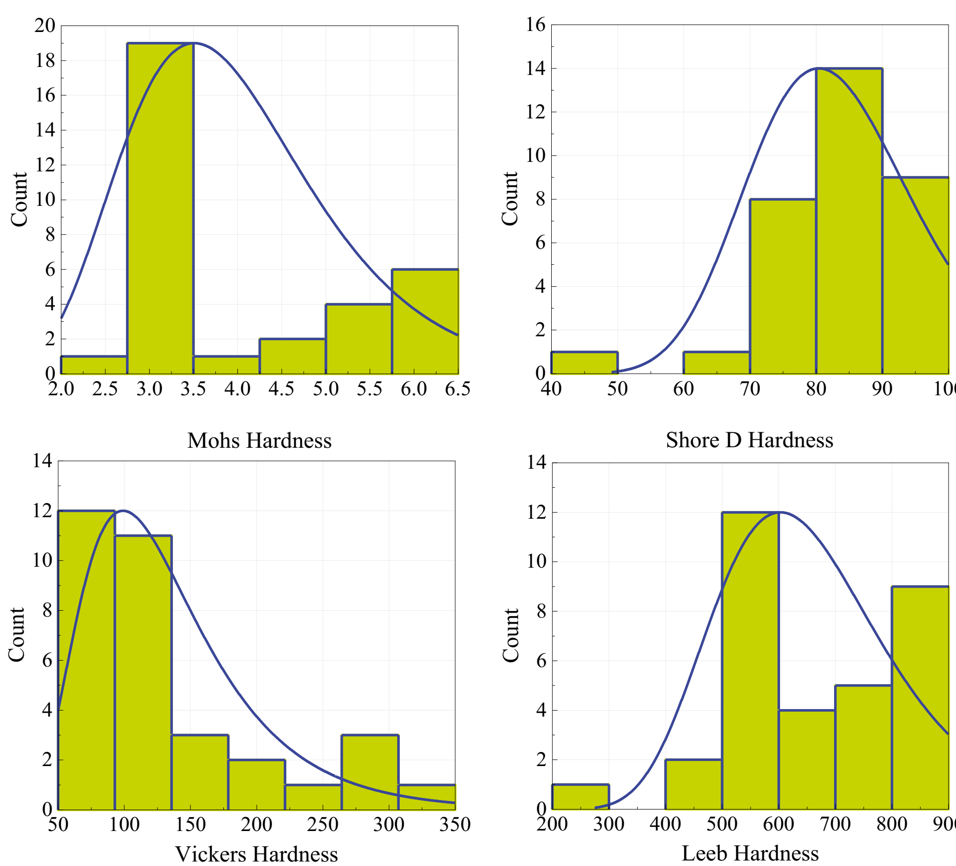

Fig. 9 Histograms of rock hardness testing results

Table 3 Statistical results of simple regression analyses in sedimentary samples

Model no	Distribution type	Variables	Coefficient of determination (R^2)	*F* value	Sig. of F	Standard error of estimate (SEE)
1	Linear	Leeb vs Mohs	0.670	38.572	0.000	0.165
2		Leeb vs Shore	0.561	24.261	0.000	6.826
3		Leeb vs Vickers	0.607	29.389	0.000	19.230
4	Logarithmic	Leeb vs Mohs	0.710	46.521	0.000	0.155
5		Leeb vs Shore	0.693	42.807	0.000	5.710
6		Leeb vs Vickers	0.503	19.250	0.000	21.629
7	Power	Leeb vs Mohs	0.750	54.926	0.000	0.049
8		Leeb vs Shore	0.708	44.086	0.000	0.091
9		Leeb vs Vickers	0.545	22.870	0.000	0.189
10	Exponential	Leeb vs Mohs	0.675	39.506	0.000	0.056
11		Leeb vs Shore	0.550	23.183	0.000	0.111
12		Leeb vs Vickers	0.640	32.877	0.000	0.170

the rock hardness class. In other words, due to the disadvantages of other hardness methods in terms of time, cost, and measurement accuracy, quick determination of the rock hardness based on the new classification system will have many applications in rock mechanics and geological engineering. Hence, by assessing the hardness methods, one can achieve valuable information about rock material and its physicomechanical characteristics by consuming the minimum time and cost.

The proposed classification is the first rock hardness classification using the Leeb portable method based on the basic Mohs method. In other words, according to the vast studies

Table 4 Statistical results of simple regression analyses in igneous samples

Model no	Distribution type	Variables	Coefficient of determination (R^2)	*F* value	Sig. of F	Standard error of estimate (SEE)
1	Linear	Leeb vs Mohs	0.811	42.871	0.000	0.244
2		Leeb vs Shore	0.799	39.836	0.000	2.754
3		Leeb vs Vickers	0.579	13.753	0.004	58.903
4	Logarithmic	Leeb vs Mohs	0.800	40.029	0.000	0.251
5		Leeb vs Shore	0.790	37.582	0.000	2.818
6		Leeb vs Vickers	0.544	11.938	0.006	61.290
7	Power	Leeb vs Mohs	0.810	42.756	0.000	0.047
8		Leeb vs Shore	0.814	42.654	0.000	0.030
9		Leeb vs Vickers	0.649	18.465	0.002	0.299
10	Exponential	Leeb vs Mohs	0.820	45.417	0.000	0.046
11		Leeb vs Shore	0.824	44.723	0.000	0.030
12		Leeb vs Vickers	0.690	21.247	0.001	0.285

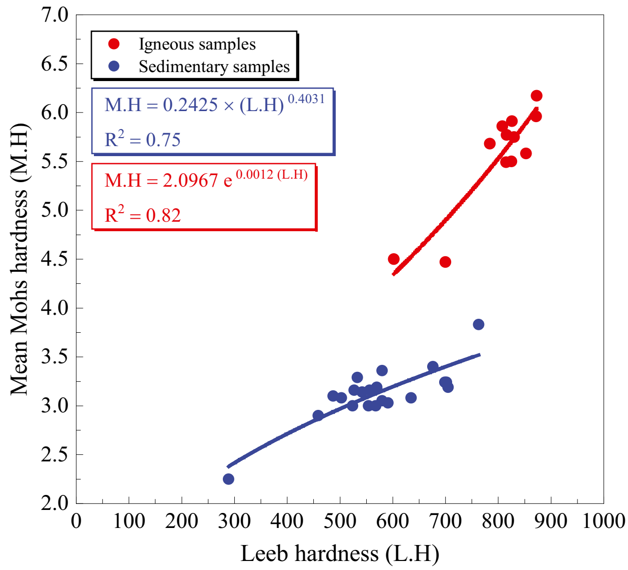

Fig. 10 Correlation between Leeb hardness and Mohs hardness of studied rocks

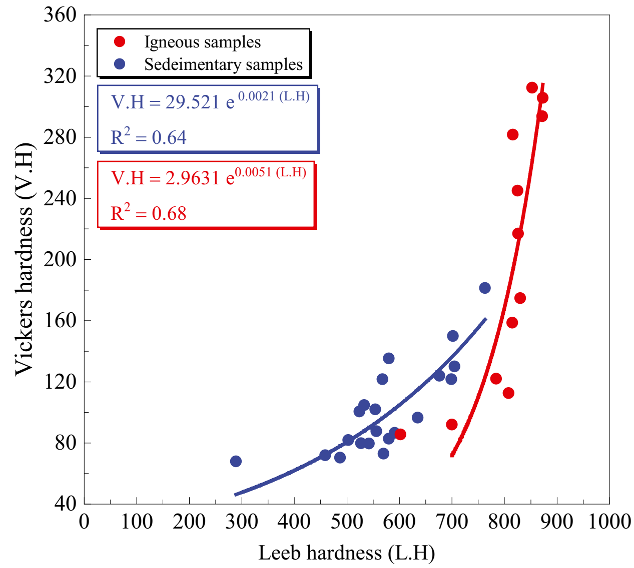

Fig. 12 Correlation between Leeb hardness and Vickers hardness of studied rocks

on the Mohs hardness of rock samples using microscopic analyses, the overlap of six classes of the Mohs classification and its corresponding classes in the Leeb method has been investigated. It is true that the Mohs method is the basic method of hardness measurement in rocks, but the remarkable things are the very short time and low cost to evaluate the hardness class of rocks using the Leeb portable method. These advantages have made the Leeb method widely used today both in the laboratory and in situ.

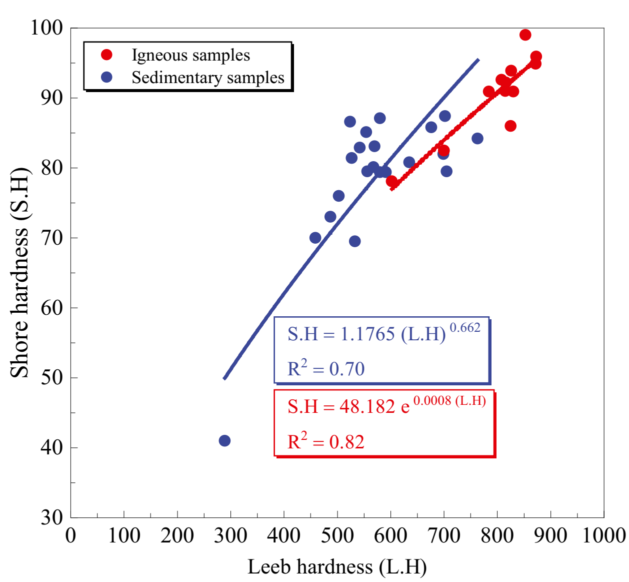

Fig. 11 Correlation between Leeb hardness and Shore hardness of studied rocks

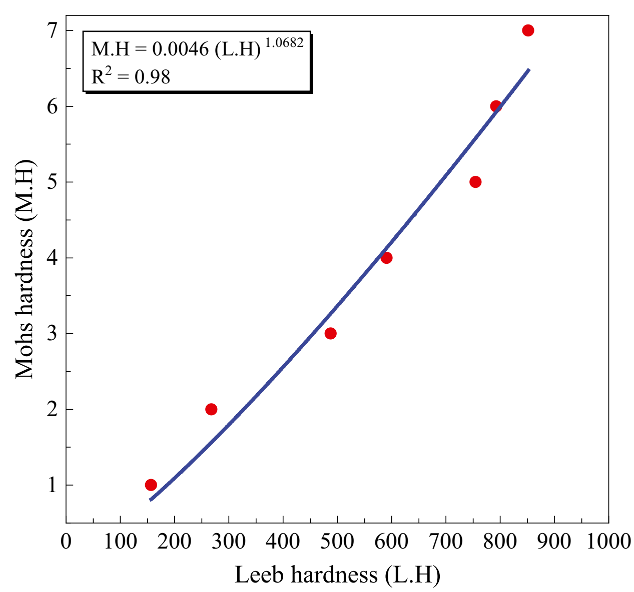

Fig. 13 Correlation between Leeb hardness and Mohs hardness of seven reference minerals

Fig. 14 Scatter diagram for interaction between the Leeb and Mohs hardness scales with a focus on reference minerals

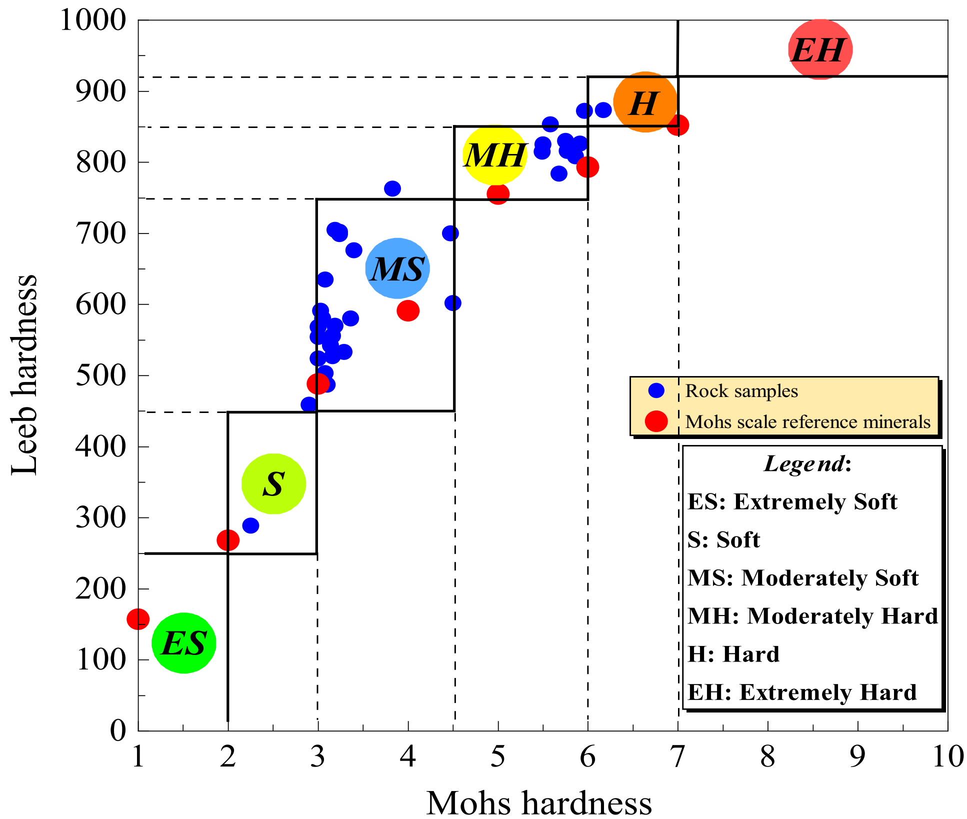

Fig. 15 Rock hardness classification using Leeb hardness method

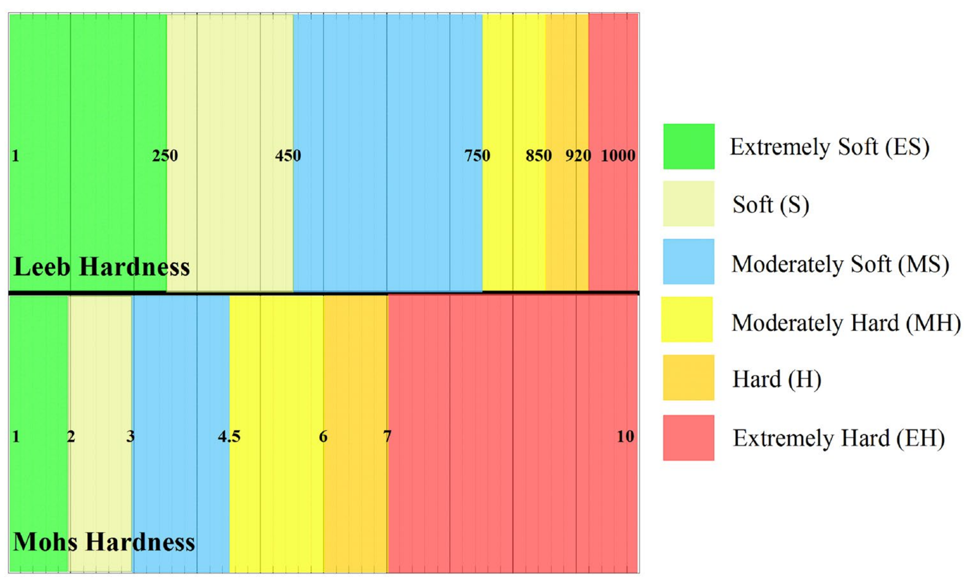

Table 5 Rock hardness classification using Leeb method

Class no	Leeb number	Hardness description
1	1–250	Extremely soft
2	250–450	Soft
3	450–750	Moderately soft
4	750–850	Moderately hard
5	850–920	Hard
6	920–1000	Extremely hard

Conclusion

As one of the most critical engineering concepts in rock mechanics and geological engineering, rock hardness has a crucial role in engineering applications, especially rocks machinability. So far, many rock hardness testing methods with different mechanisms and standards have been developed and applied. Thus, providing a fast testing method leading to the rock hardness class seems necessary and has been a challenge for rock engineering experts for decades. Determining the hardness of rocks using the Mohs hardness scale is a time-consuming testing process (preparation of thin sections of rock samples, their microscopic studies, and then the determination of mean Mohs hardness and its class). Additionally, so far, no classification system has been proposed using portable methods that can determine the harness class of the rocks quickly. Therefore, the new classification system presented in this paper could be used as a preliminary guide to determine the rock hardness class.

This paper presents a new engineering classification based on experimental observations, statistical models, and theoretical concepts using the Leeb dynamic hardness method. The laboratory studies' results show that, due to portable, accurate, low-cost, and non-destructive origin, the Leeb method can be applied to evaluate rock hardness classification properly. The main advantage of this new classification is its simplicity. Based on achieved results, rock hardness is classified into six classes' viewpoint of Leeb scale from extremely soft to extremely hard, as shown in Table 5.

This paper's results have been achieved based on the hardness testing on a cubic block of rock samples with non-rough surfaces and sides. To expand this research in geological, mining, and civil applications, it is essential to study the Leeb hardness of rough non-cubic samples and core samples. In the case of further studies, Leeb's hardness can potentially support any quick assessment of rock hardness with a significant level of reliability. Hence, in the continuation of the current paper, it is recommended to investigate the effect of rock texture and surface roughness on the results of Leeb hardness testing methods in future studies.

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