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ORIGINAL PAPER

# Effect of quantitative textural specifications on Vickers hardness of limestones

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## Abstract

It is well-known that the indentation hardness property is influenced by micro-fabric characteristics. The effect of textural characteristics on Vickers indentation hardness is attempted to be interpreted in this research. For this purpose, 12 fresh limestone samples from various quarries were tested to determine the Vickers hardness. Thereafter, quantitative textural parameters were identified and characterized using image processing techniques and micro-fabric analysis based on microphotographs of thin sections. Microphotographs of the thin sections were reviewed and digital boundaries of the grains were clarified and drawn. After preparation and filtering of the digitized thin sections, four basic properties of each grain, including maximum diameter, minimum diameter, area, and perimeter, were calculated with the ImageJ software. These parameters were then analyzed statistically and used to obtain seven indices, including equivalent diameter, grain compactness, shape factor, aspect ratio, grain interlocking index, grain size homogeneity, and texture coefficient. Experimental equations were developed and the results showed that Vickers indentation hardness was strongly influenced by textural properties. In addition, it was found that in the studied limestones, the three parameters of grain size, aspect ratio, and texture coefficient have the greatest effect on Vickers hardness.

**Keywords** Vickers indentation hardness · Textural characteristics · ImageJ software · Grain size · Aspect ratio

## Abbreviations

| | |
|---|---|
| $A$ | Grain area |
| $P$ | Grain perimeter |
| $D_{max}$ | Major axis length |
| $D_{min}$ | Minor axis length |
| $D_{equi}$ | Equivalent diameter (or grain size) |
| $TC$ | Texture coefficient |
| $N_1$ | Number of grains with an aspect ratio greater than 2 |
| $AR_1$ | Arithmetic mean of the aspect ratio of $N_1$ grains |
| $AW$ | Area weighting (grain packing density) |
| $F$ | Applied force in Vickers hardness test |
| $d_1$ and $d_2$ | Diagonal lengths of indentation |
| $MAPE$ | Mean absolute percentage error |
| $y$ | Experimental values of Vickers hardness |
| $y_{avg}$ | Mean measured values of Vickers hardness |
| $AR$ | Aspect ratio |
| $SF$ | Shape factor |
| $C$ | Grain compactness |
| $t$ | Grain size homogeneity |
| $g$ | Grain interlocking index |
| $N_0$ | Number of grains with an aspect ratio less than 2 |
| $FF_o$ | Arithmetic mean of the shape factor of all $N_0$ grains |
| $AF_1$ | Angle factor orientation for all $N_1$ grains |
| $V.H$ | Vickers hardness |
| $d_v$ | Mean diagonal length of indentation |
| $VAF$ | Variance account for |
| $NRMSE$ | Normalized root mean square error |
| $y'$ | Calculated values of Vickers hardness |
| $N$ | Number of rock samples in statistical analyses |

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## Introduction

Hardness is one of the most investigated physical characteristics of rocks and minerals and has been relevant throughout recorded history to current advanced rock engineering projects (Ghorbani et al. 2022b). Hardness indicates the rock's resistance to penetration, scratch, or permanent deformation (Heiniö 1999; Demirdag et al. 2009). In addition, rock hardness is the first resistance that must be overcome during the excavation process (Jimeno et al. 1995). In general, rock hardness testing methods are classified into four mechanisms: rebound, indentation, scratch, and grinding. Among these, indentation hardness tests such as the Vickers method have been widely used in various rock mechanics and geological studies such as drilling (Bameri et al. 2021), sawability assessment (Sánchez Delgado et al. 2005; Yılmaz 2011), assessment of specific energy of cutting tools (Aydin et al. 2013a), predicting the lifetime of disk cutters of TBM (Hassanpour et al. 2015), and cutting tools (Aydin et al. 2013b; Majeed et al. 2020). Additionally, the estimation of rock mechanical properties using Vickers hardness is also used in rock mechanics studies. Teymen (2021) has investigated estimating the uniaxial compressive strength (UCS) and elastic modulus (E) of 93 different specimens from the Vickers hardness test. The results show that there are significant relationships between UCS and E with the Vickers hardness test. Therefore, due to the importance and role of hardness and also the wide range of applications of hardness tests, it is necessary to investigate the effect of various properties of rock materials, especially rock texture, on the Vickers hardness. There are other studies on the effect of textural properties on Schmidt rebound hardness. Khajevand (2021) evaluated the influence of petrographic and textural characteristics on the geotechnical properties of some carbonate rock samples. The results showed that the texture coefficient has a significant effect on Schmidt hardness with an $R^2$ of 0.92. Diamantis et al. (2021) have studied the effect of texture coefficient on Schmidt rebound hardness of limestones and mudstones. The regression analyses showed that the correlations between Schmidt hardness and texture coefficient in limestones and mudstones have logarithmic and linear relationships with $R^2$ of 0.65 and 0.8, respectively. Furthermore, Ersoy and Waller (1995) proposed that the shore rebound hardness and Mohs hardness are related to *TC* with $R^2$ of 0.687 and 0.135, respectively.

Micro-fabric features are the main factor in determining the engineering properties of rocks especially sedimentary samples (Kamani and Ajalloeian 2019). Meanwhile, rock hardness is also mainly influenced by mineral composition and texture (size and shape descriptors and fabric coefficients). The texture is of high importance in the evaluation of the mechanical properties of rocks (Ersoy and Waller 1995). The texture is also described in petrologic meaning as the size and the shape of the mineral particles and their distribution in space. In addition, the texture of rocks gives an idea about the mechanism for the formation of rock fabrics (Leiss et al. 2000) and also control the anisotropic physical properties of rocks.

Limestones are one of the most abundant sedimentary rocks which are very important in the field of petroleum engineering, mining extraction, rock mechanics, and building stone industry. These rocks do not have much difference in mineralogy; nevertheless, the texture is very variable. Additionally, from the view point of rock mechanics, limestones are challenging rocks due to following reasons:

- The Mohs hardness of limestone ranges from 2 to 4 (medium soft and medium classes)
- Limestone samples are classified in a wide range of UCS (R4, strong grade: 50–100 MPa, and R5, very strong grade: 100–250 MPa) (Ameratunga et al. 2016)
- Limestones have a wide variety of texture and chemical composition
- Hardness testing on limestone samples is challenging and could produce different results in a same rock sample

For this purpose, the limestone samples were used in this study to clarify the effects of textural specifications on Vickers hardness.

Based on the literature review, no comprehensive studies have been performed on the effect of rock textural properties on the Vickers indentation hardness in rock materials, and very little attention has been paid to this topic and so this is the main motivation for the current study. Accordingly, the current study presents the Vickers indentation hardness and textural characteristics of limestone samples. The main goal is to establish some quantitative relationships between Vickers hardness and textural characteristics. For this reason, 12 limestone block samples were tested to determine Vickers hardness. The petrographic characteristics were also investigated using an Olympus polarization microscope with crossed polarized light (XPL). The results were statistically examined, and the best-fit equations were used to characterize the relationships between them. It should be mentioned that, using scientific evidence, attempts were made to evaluate in detail the effect of textural characteristics on the Vickers hardness of the samples.

## Materials

In the current research, 12 limestone samples were selected from various quarries in Iran. Block samples with dimensions of approximately $20 \times 20 \times 20$ cm were transferred to the laboratory for testing. All the blocks were fresh and unweathered. These block samples were cut and prepared in appropriate sizes for Vickers tests, and thin sections of each rock sample were prepared for microscopic examinations and textural characteristics determination. The petrographic examination was performed using optical microscope with high resolutions. Quantitative analyses were performed for

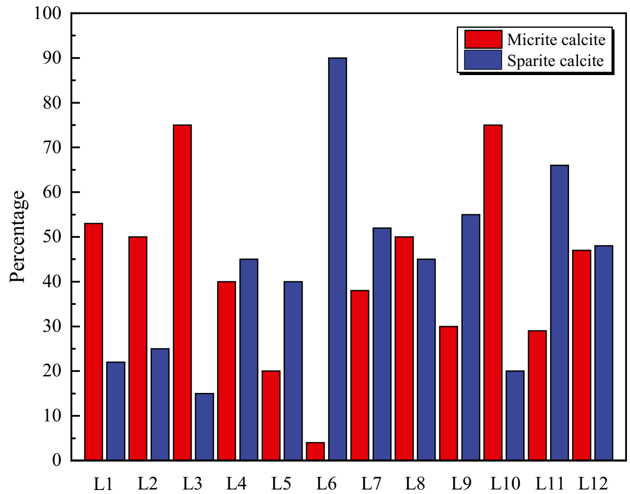



**Fig. 1** Percentage of sparite and micrite calcites in the studied limestone samples

textural and mineralogical identifications using representative thin sections. Sparite and micrite calcites are the two main minerals found in the studied limestone samples. The percentage of minerals in each sample is calculated based on the mineralogical interpretation of thin sections. Except for samples L1, L2, and L5, all the investigated limestones include more than 80% of the sparite and micrite calcites, as shown in Fig. 1.

## Laboratorial experiments

### Vickers hardness test

Vickers method is a hardness test that determines the material's hardness against the square-based pyramidal diamond. This method was first introduced by Smith and Sandly (1922) as an alternative to the Brinell method.

The Vickers hardness test is performed using a square-based pyramidal-shaped diamond indenter with face angles of 136° by applying a certain load level. After applying this load level, the diagonal length indentation is measured by a microscopic with an accuracy of 0.1 mm. The Vickers number is based upon the force divided by the surface area of the indentation. The Vickers hardness number is calculated as Eqs. (1) and (2) (ASTM E92-16 2016).

$$V.H = \frac{F}{A} = 1.8544\frac{\mathrm{F}}{\mathrm{d}_{\mathrm{v}}^2} \quad (1)$$

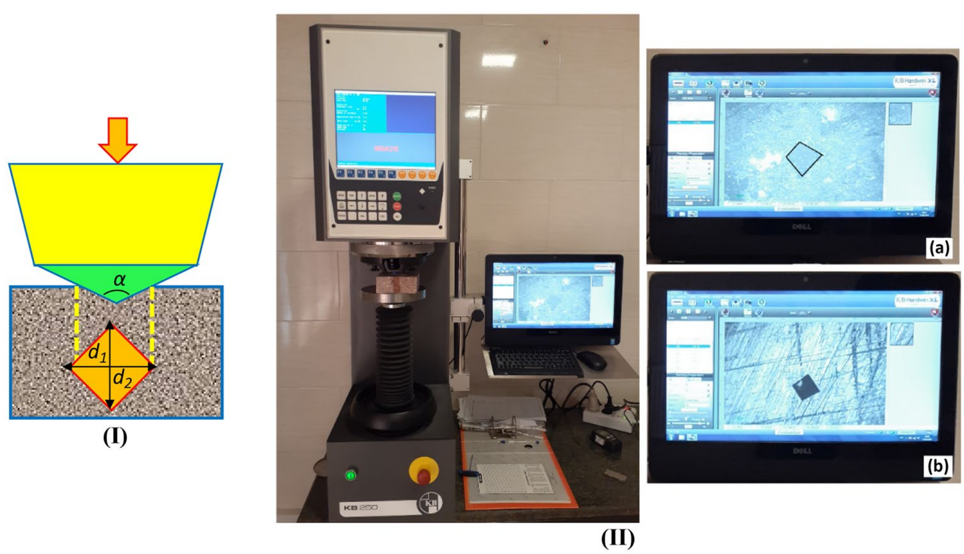
$$d_v = \frac{d_1 + d_2}{2} \quad (2)$$

where $F$: force in $Kgf$, $d_v$: mean diagonal length of indentation in mm, $d_1$ and $d_2$: diagonal lengths of indentation in mm.

In this study, the block samples of the dimensions of $10 \times 10 \times 5$ cm (Ghorbani et al. 2022a) were tested by an advanced universal hardness testing machine, KB Prüftechnik (Fig. 2(II)). This device was equipped with a USB camera, high load stage range, and associated KB HardWin XL software package.

Due to the laboratory observations during the Vickers tests, and as it was reported by other researchers (Xie and Tamaki 2007), it was found that the indentation area is not identified clearly in some rock samples, as shown in Fig. 2(II). Thus, 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 are shown in Fig. 3. Figure 3 presents the comparative diagrams

**Fig. 2** Vickers indentation hardness test (I) schematic of this test. (II) Applied universal hardness testing machine



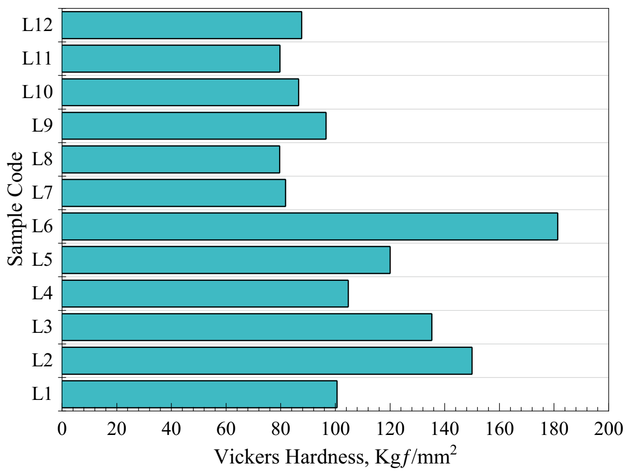



**Fig. 3** Bar diagram of mean values of Vickers hardness for studied limestones

of the values of Vickers hardness for the studied limestones. As can be seen, the values of Vickers hardness for the studied limestone samples are up to about 180 Kg*f*/mm$^2$.

## Textural characteristics

The texture of rocks is a term representing the mineral grains, grain sizes, and matrices of rocks. When the textural properties of rocks are evaluated, the geometric properties of the mineral grains and the relationship between grains and the matrix should be analyzed well (Lamarche et al. 2012).

Rock texture can be quantified using geometrical features. Grain shape and size can be quantified by the major axis length, minor axis length, grain area, and grain perimeter, which are used to formulate several properties (see Table 1). In general, rock micro-fabric represents the three groups of descriptors including size and shape descriptors and fabric coefficients which are shown in Fig. 4.

Rock micro-fabric characteristics are applied for quantifying rock textural conditions and are measured by image processing of thin sections. The combination of the thin sections with computerized programs has become a common method in geology (Petruk 1989). This program permits fast measurement and quantitative analysis of thin sections' properties (Reedy 2006). Various techniques of image processing have been developed to extract the rock micro-fabric characteristics. Among these methods, the segmentation technique of rock photomicrographs allows for quantifying the specimen's inner structure (Aligholi et al. 2017).

The system of petrographic image analysis (i.e., measurement of certain microstructural parameters in thin section using specialized software) adopted in this study is based on the manual pre-processing of the microphotograph of the thin section. During the micro-fabric analysis of the thin section, four basic characteristics, including grain perimeter and grain area and length of minor and major axes, were measured using ImageJ software and then all mentioned textural parameters (Table 1) were applied in regression analyses. The digitized microphotographs of limestone samples are shown in Fig. 5. As is apparent in Table 1, during the quantitative analysis of microphotographs of thin sections, most of the parameters are defined based on grain

**Table 1** Rock micro-fabric characteristics used in the analysis (Howarth and Rowlands 1987; Přikryl 2006)

| Parameter | Computation | Meaning of parameter |
|---|---|---|
| Area | Using ImageJ software | Cross-section area |
| Perimeter | | Length of grain boundary |
| Major axis length | | - |
| Minor axis length | | |
| Equivalent diameter | $D_{equi} = \sqrt{\frac{4A_i}{\pi}}$ | Grain size |
| Aspect ratio | $AR = \frac{D_{max}}{D_{min}}$ | Grain ellipticity |
| Shape factor | $SF = \frac{4\pi A_i}{P^2}$ | The circularity of grain cross-section |
| Grain compactness | $C = \frac{P^2}{A_i}$ | The shape of the grain cross-section |
| Grain size homogeneity | $t = \frac{A_{avg}}{\sqrt{\sum (A_i - A_{avg})^2}}$ | Grain size distribution |
| Interlocking index | $g = \frac{1}{n} \times \sum \frac{P_i}{\sqrt{A_i}}$ | The complexity of grain–grain relationships |
| Texture coefficient | $TC = AW\left[\left(\frac{N_0}{N_0+N_1} \cdot \frac{1}{FF_0}\right) + \left(\frac{N_1}{N_0+N_1} .AR_1 .AF_1\right)\right]$ | Assessing the rock fabric |

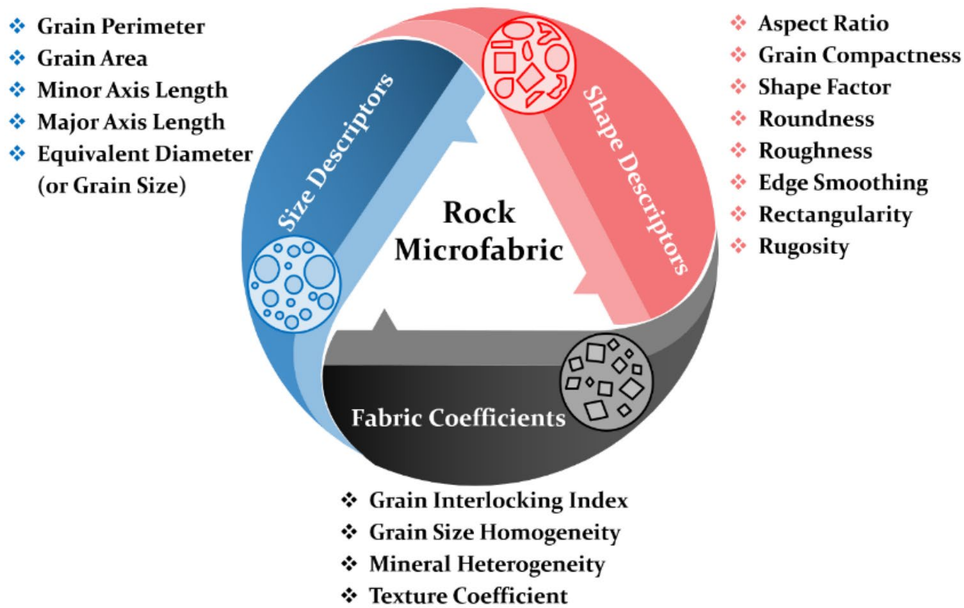



**Fig. 4** Rock micro-fabric characteristics and interactions

area, perimeter, maximum, and minimum lengths. However, each parameter represents a special feature related to the mechanical, geometrical, or structural condition of the rock micro-fabric. After analyzing the four above parameters, all other basic textural characteristics of the limestone samples were calculated based on the equations presented in Table 1. The values of seven calculated textural parameters of the studied limestones are shown in Fig. 6. As can be seen in this figure, seven various rock textural parameters have different values and ranges. In other words, the 12 studied limestone samples have different behaviors from a micro-fabric perspective.

## Statistical analyses and discussions

To evaluate the effect of textural characteristics on Vickers indentation hardness of the limestones, regression analysis was used. For this purpose, the correlations between Vickers hardness and the seven mentioned textural characteristics were determined. Linear, logarithmic, exponential, and power curve fitting approximations were tried. The best equations were selected based on the highest correlation coefficient ($R^2$) values. The flowchart of the applied methodology for assessing the effect of textural characteristics on Vickers hardness is presented in Fig. 7.

Equivalent diameter (or grain size) is a significant microstructure parameter that affects the physico-mechanical properties of rocks especially, hardness with indentation mechanism, and also it is the most fundamental property of sedimentary rocks. Figure 8 shows the decreasing behavior in relation to the Vickers hardness with increasing grain equivalent diameter in limestone samples. The relationship followed the logarithmic function with a strong correlation coefficient of 0.86. The relationship between Vickers hardness and grain size can be interpreted using the concept of rock strength. In general, it is clear that the indentation hardness is closely related to the strength of the rocks. There are various studies on the relationship between grain size and rock strength on sedimentary rock samples that show that with increasing grain size, rock strength decreases (Palchik and Hatzor 2000; Přikryl 2001; Yu et al. 2018). Brace (1961) has explained one of the reasons for the increase in rock strength due to the decrease in grain size with Griffith's theory. In this theory, Griffith's crack length is considered to be proportional to the grain size. By increasing the grain size, grain boundaries, which are widely assumed to be the predominant source of stress-concentrating flaws, increase. Consequently, with increasing crack length, strength decreases (Yu et al. 2018). Therefore, it can be concluded that with increasing grain size, the indentation hardness methods such as Vickers hardness decrease. The results of this study also indicate this. Moreover, Tiskatine et al. (2016) investigated the effect of grain size on the Vickers hardness of limestone samples. The results of this study showed that with the increase in the grain size of limestone and marble samples, the Vickers hardness decreases logarithmically. Therefore, the results of the current research are consistent with the previous study and indicate a logarithmic decrease in Vickers hardness with increasing the grain size of limestone samples.

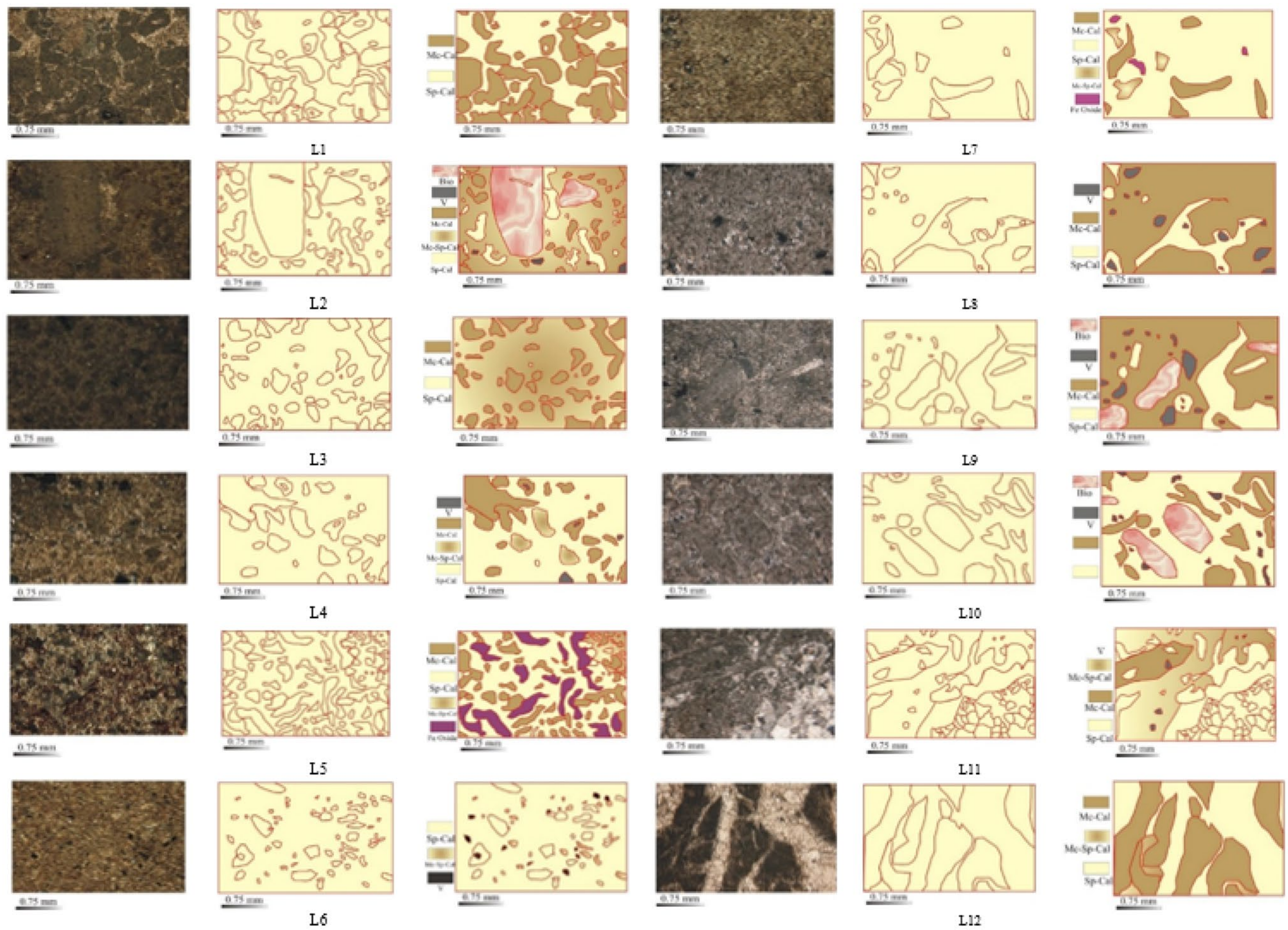



**Fig. 5** Digitized images of studied limestone samples for extraction of textural characteristics

According to the classification provided by Osanloo (1998), the grain size of rock samples is divided into six classes as shown in Table 2. Based on this classification, all studied limestone samples are in two classes: very fine-grained and fine-grained (Fig. 8). It should be noted that, according to the analyses, Vickers hardness of very fine-grained samples is more sensitive to grain size than fine-grained samples. In other words, the slopes of the curve showed that the Vickers indentation hardness in very fine-grained rocks was more sensitive to the mean equivalent diameter than in fine-grained rocks. In the very fine-grained rocks ($D_{equi}$<0.25 mm), the Vickers hardness appeared to be affected more by grain size (see Fig. 8). Therefore, it can be concluded that the smaller the grain size of the rock, the greater the indentation hardness and consequently the strength properties of the sample. This point is also more tangible and important in the topics of rock drilling and wear assessment of drilling tools. Because of the very fine-grained rock, the higher the indentation hardness, strength, energy consumption, wear of drilling tools, and the lower the drilling rate.

The shape descriptors of limestone samples have shown different behaviors against Vickers hardness. Generally, the aspect ratio of the rock grains increases with increasing grain interlocking (Hoseinie et al. 2019). On the other hand, the macroscopic mechanical behavior of rock as a granular material is controlled by the interaction forces between grains (Jongchansitto et al. 2017). Also, more force is required to penetrate between grains. Therefore, based on the above descriptions, it can be predicted that the rock strength and then Vickers hardness increases with increasing grain interlocking and the grain aspect ratio, which the results of this study also indicate this fact (see Fig. 9).

The analyses showed that Vickers indentation hardness increased with increasing grain compactness (Fig. 10). This result was predictable because the more compact the

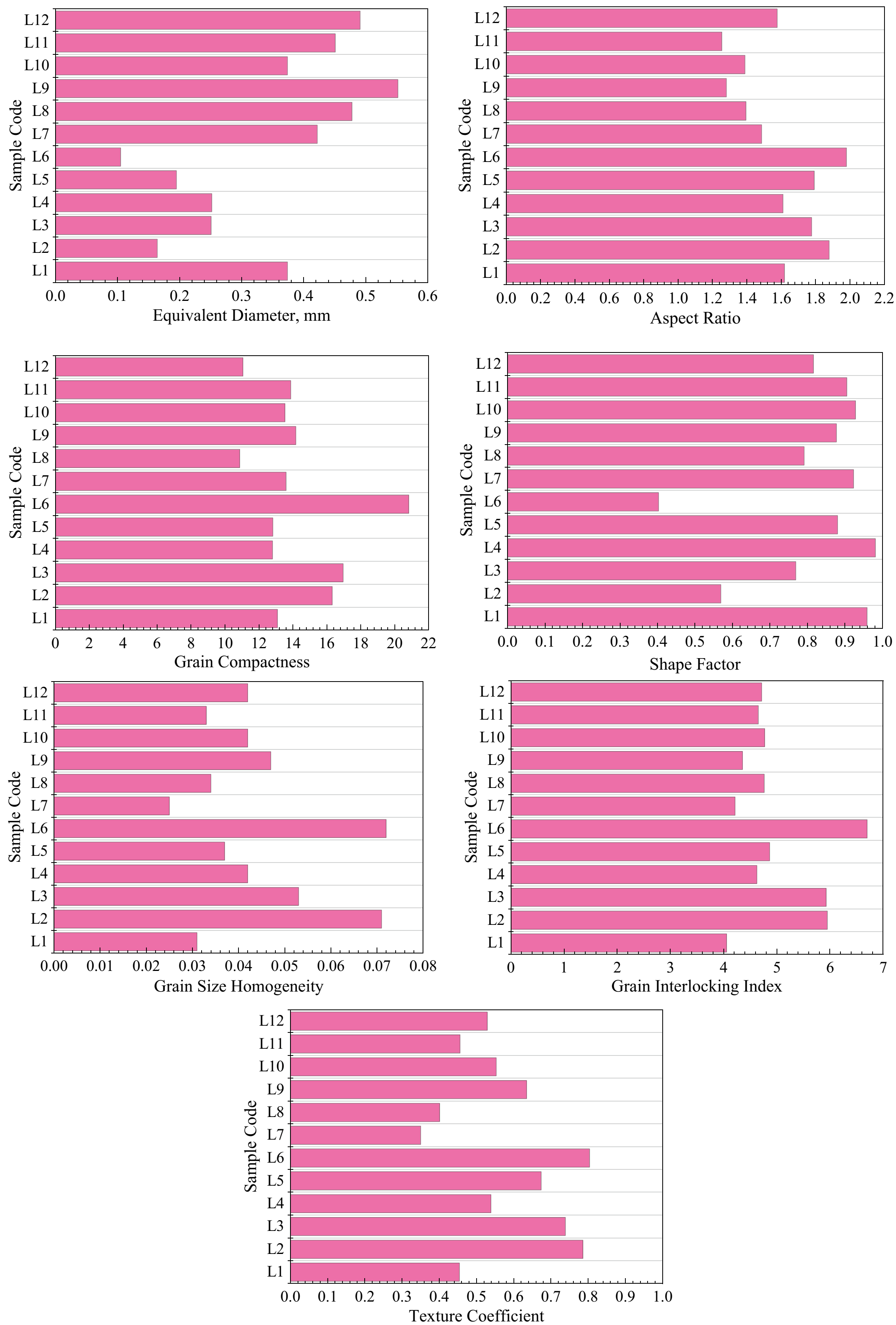
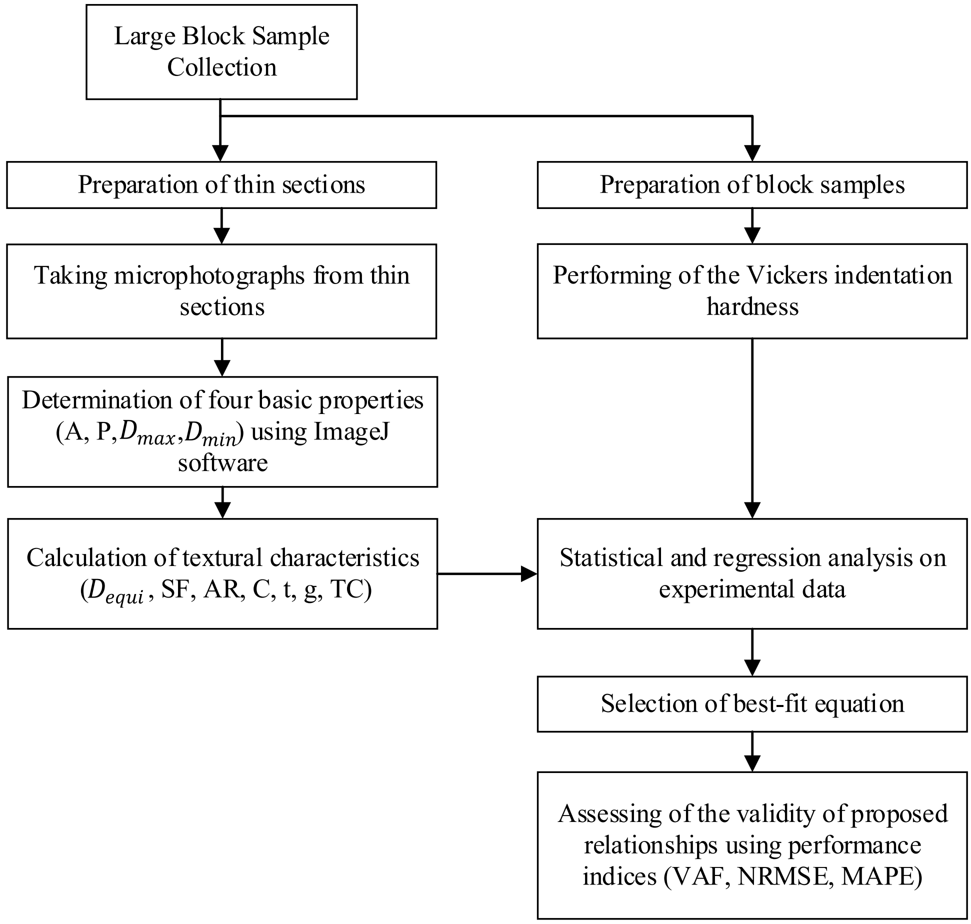



**Fig. 6** Bar diagram of textural characteristics values of studied limestone samples

**Fig. 7** Flowchart of applied methodology




grains of the rock, makes it denser. On the other hand, it can be said that the Vickers hardness is a function of the density of the rocks. In general, when the constituent grains of a rock sample are placed in a compact state of the rock texture, the porosity of the whole rock will be partially low, and the sample will be denser. Accordingly, when the density of the rock sample is high, a high level of force is required by the Vickers hardness instrument to penetrate the rock sample. Therefore, the Vickers hardness of the rock increases.

Additionally, further analyses were performed to determine the relationship between Vickers indentation hardness, density, and grain compactness. It should be noted that density tests on 12 limestone samples were performed according to ISRM standard (ISRM 1981). Figure 11 shows the variation of Vickers indentation hardness with density and grain compactness for studied

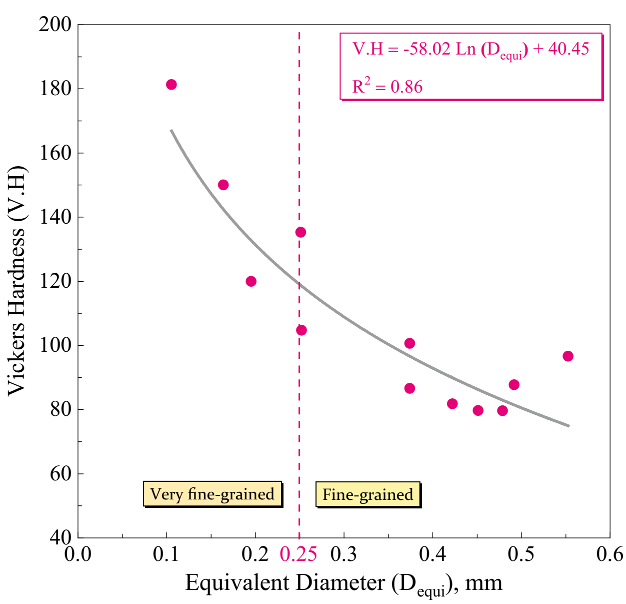



**Fig. 8** The effect of equivalent diameter on Vickers indentation hardness

**Table 2** Grain size classification of rock samples (Osanloo 1998)

| Class | Grain size (mm) | Description |
|---|---|---|
| I | < 0.25 | Very fine-grained |
| II | 0.25–2 | Fine-grained |
| III | 2–5 | Medium-grained |
| IV | 5–10 | Coarse-grained |
| V | > 10 | Very coarse-grained |

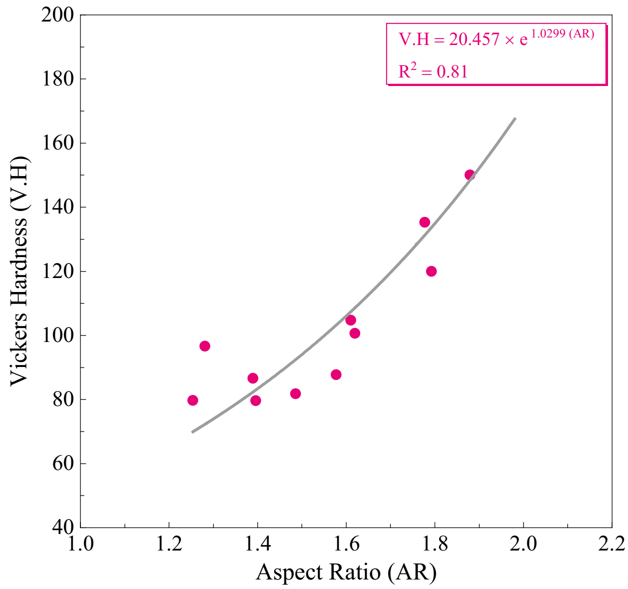



**Fig. 9** Correlation between Vickers hardness and aspect ratio

limestones. With increasing grain compactness and density of rock samples, the Vickers hardness increased. Based on the fitting surface, the effect of grain compaction on Vickers indentation hardness seems to be more significant than density. Hence, in general, it can be concluded that there is a reasonable interaction between rock grain compactness, density, and Vickers indentation hardness.

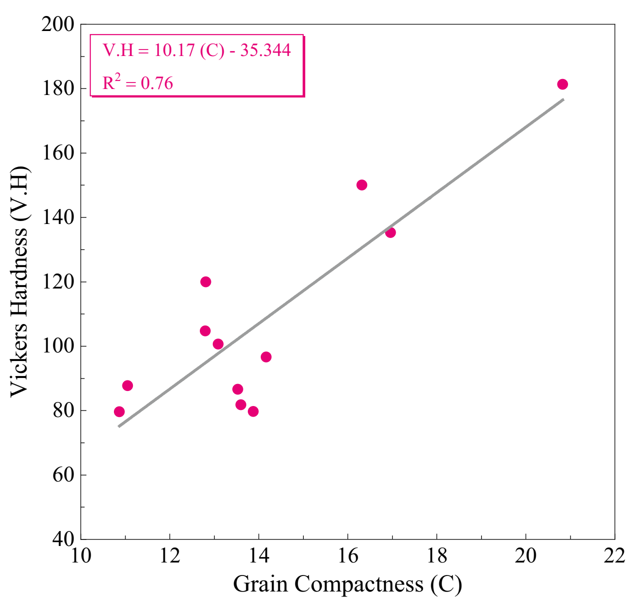



**Fig. 10** Correlation between Vickers hardness and grain compactness

The shape factor demonstrates the circularity of grain cross-section (Přikryl 2006). In other words, shape factor is a measure of a grains' deviation from circularity. This deviation may occur in two ways; elongation of the shape, or increased roughness of the grains' perimeter. Hence, with increasing shape factor, the grain interlocking and grain compactness decrease.

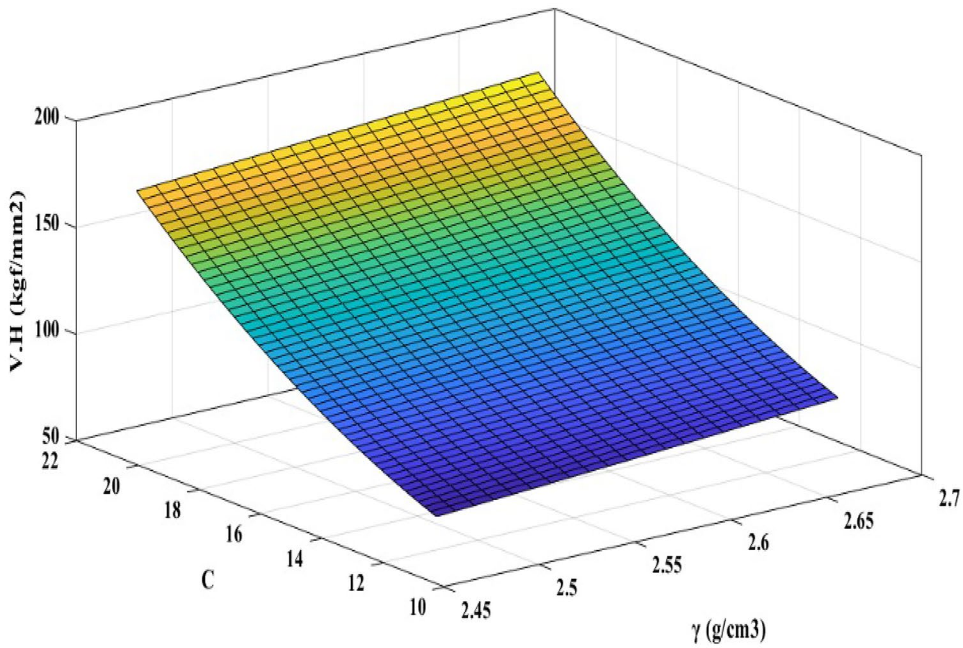
Therefore, as shown in Fig. 12, the Vickers hardness decreased with increasing shape factor. With increasing the shape factor, the circularity of the grains increased; and therefore, it has led to a decrease in Vickers indentation hardness. This result can be examined from a mechanical point of view in more detail. Samples with complex grain shapes are generally stronger, mainly because interlocking between mineral grains can increase the internal friction angle (Cho et al. 2006; Han et al. 2019). In other words, the strength and consequently indentation hardness of the rock materials have meaningful relationships with the internal friction angle. Therefore, an increase in the friction of rock-forming minerals can increase the overall strength and consequently the overall rock hardness, especially the indentation mechanism.

The correlation between Vickers hardness and the grain interlocking index followed a linear function (see Fig. 13). The Vickers hardness increased with increasing grain interlocking. With increasing grain interlocking, the grain network becomes increasingly complex and dense (Hoseinie et al. 2019). In other words, a high interlocking index or high packing density shows the strong and complicated relationship of grains toward each other's that causes an increase in the strength of rocks. Additionally, based on Hoek's point of view, the high grain interlocking in rocks leads to an increase of applied stress to drive the boundary cracks (Hoek 1965). Therefore, the indentation requires more power to overcome the grain-grain interactions of the dense network, and thus, the Vickers indentation hardness increases.

In general, in igneous and sedimentary rocks, with tightly packed and well cemented grains, severe interlocking of the grains can be occurred. It results in a considerable increase in the applied force required to generate the diagonal length of indentation ($d_v$) on the grains. Also, when the grains are locked together in a very compact rock texture, too much force is required to create an indentation during the Vickers test. Therefore, in such texture and grain orientation, the Vickers indentation hardness increases.

Increasing grain size homogeneity results in increasing homogeneity of the whole structure of the rock material (Hoseinie et al. 2019). In addition, high

**Fig. 11** 3D surface plot between Vickers hardness, density, and grain compactness for studied limestones




homogeneity is associated with higher strength and resistance to indentation. In other words, it can be said that more homogeneous rocks have a denser structure and less porosity, and this increases the overall strength and hardness of the rock. As shown in Fig. 14, with increasing grain size homogeneity in studied limestone samples, the Vickers indentation hardness increased linearly.

Finally, texture coefficient as a quantitative index was also applied in regression analysis. In general, the texture coefficient values are high in rocks with a large volume of grains and the opposite (Diamantis et al. 2021). The

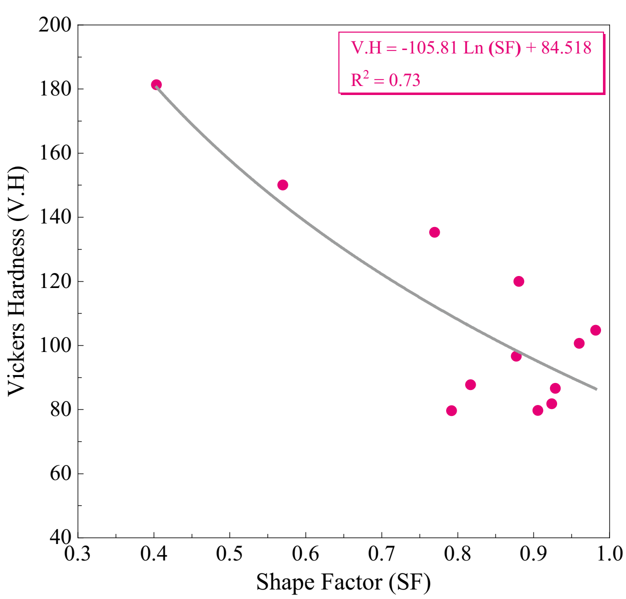



**Fig. 12** Correlation between Vickers hardness and shape factor

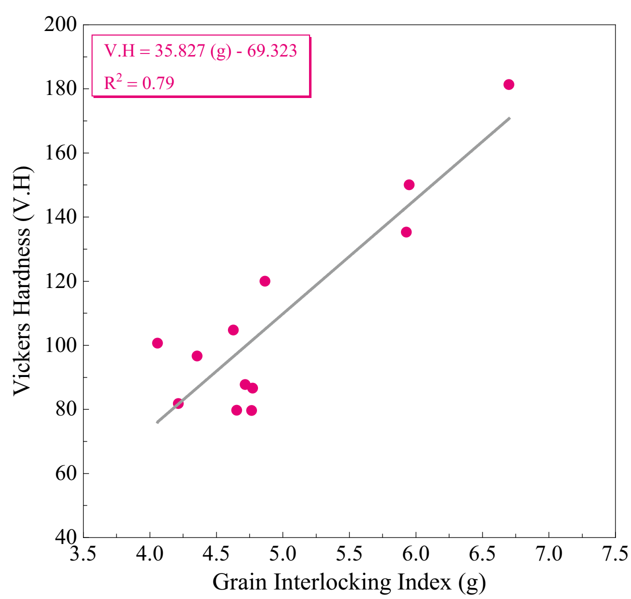



**Fig. 13** Correlation between Vickers hardness and grain interlocking index

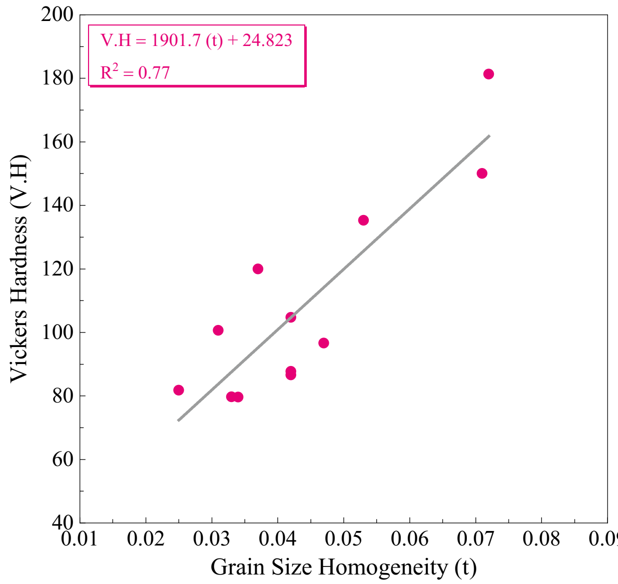



**Fig. 14** Correlation between Vickers hardness and grain size homogeneity

results of the analysis reveal that, with increasing the *TC*, the Vickers indentation hardness increases. As can be seen in Fig. 15, the relationships between them follow the exponential function with a reasonable correlation coefficient of 0.82. However, other studies have been focused on relationship between the textural characteristics of limestones and the Schmidt and Shore hardness. Diamantis et al. (2021) investigated the effect of texture coefficient on the Schmidt hardness of limestones.

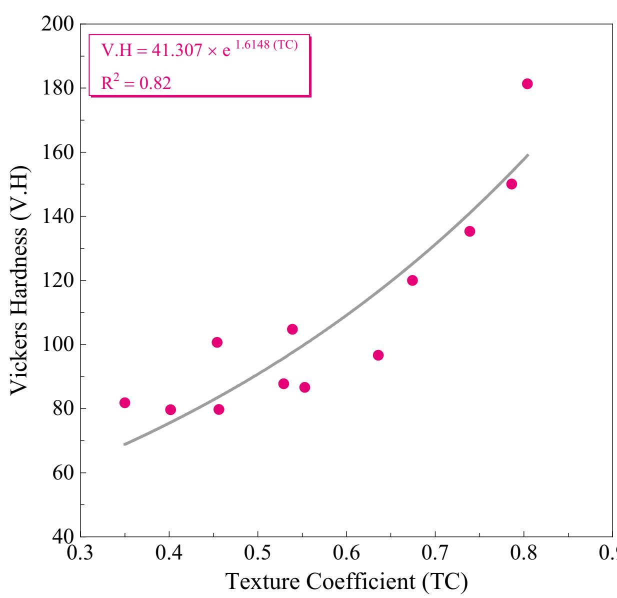



**Fig. 15** Correlation between Vickers hardness and texture coefficient

They showed that with the increase of texture coefficient, Schmidt dynamic hardness increases logarithmically. Comakli and Cayirli (2019) also found a good linear relationship between Schmidt hardness and *TC*.

## Accuracy and validation of presented regression equations

In the previous section, the quality of the developed equations was analyzed by the $R^2$ values. In addition to these, there are various other indicators for this purpose. In this study, the reliability of the developed relationships was evaluated by comparing the obtained performance indices including variance account for (*VAF*), mean absolute percentage error (*MAPE*), and normalized root mean square error (*NRMSE*). The *NRMSE*, *VAF*, and *MAPE* are calculated using Eqs. (3–5), respectively (Khajevand 2021). The model will be excellent if $R^2 = 100\%$, $NRMSE = 0$, $VAF = 100\%$, and $MAPE = 0$. The *VAF* is a statistical indicator which is used to measure preciseness of the prediction method, and the one with high *VAF* denotes high predictive performance for a given dataset. The *MAPE* is a measure of prediction accuracy of a forecasting method and usually expresses the accuracy as a percentage. Additionally, the *NRMSE*, also called a scatter index, is a statistical error indicator. Generally, lower *NRMSE* values indicate less residual variance for a model.

$$NRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y - y')^2}}{y_{avg}} \tag{3}$$

$$VAF = \left[1 - \frac{var(y - y')}{var(y')}\right] \times 100 \tag{4}$$

$$MAPE = \left[\frac{1}{N}\sum_{i=1}^{N}\left|\frac{y - y'}{y}\right|\right] \times 100 \tag{5}$$

The values of $R^2$, *VAF*, *NRMSE*, and *MAPE* for each regression equation are given in Table 3. The comparison of the regression equations reveals that Eqs. (6), (7), and (12) exhibit lower error rates than other equations. In other words, Eqs. (6), (7), and (12), which relate Vickers hardness with equivalent diameter, aspect ratio, and texture coefficient, are valid and have a high predictive capacity. This means that the calculated statistical indices show that the three parameters of equivalent diameter, aspect ratio, and texture coefficient have the greatest effect on Vickers hardness.

**Table 3** Statistical indexes for regression equations

| Equation no | Parameter | Distribution type | Equation | $R^2$ | *VAF* | *NRMES* | *MAPE* (%) |
|---|---|---|---|---|---|---|---|
| 6 | V.H-$D_{equi}$ | Logarithmic | $V.H = -58.02Ln(D_{equi}) + 40.45$ | 0.86 | 83.802 | 0.105 | 9.681 |
| 7 | V.H-AR | Exponential | $V.H = 20.457 \times e^{1.0299(AR)}$ | 0.81 | 77.244 | 0.111 | 9.457 |
| 8 | V.H-C | Linear | V.H = 10.17(C)−35.344 | 0.76 | 67.554 | 0.140 | 13.083 |
| 9 | V.H-SF | Logarithmic | V.H = −105.81Ln(SF)+84.518 | 0.73 | 62.112 | 0.148 | 14.020 |
| 10 | V.H-g | Linear | V.H = 35.827(g)−69.323 | 0.79 | 73.773 | 0.129 | 12.627 |
| 11 | V.H-t | Linear | V.H = 1901.7(t)+24.823 | 0.77 | 69.695 | 0.136 | 12.853 |
| 12 | V.H-TC | Exponential | $V.H = 41.307 \times e^{1.614(TC)}$ | 0.82 | 75.203 | 0.117 | 9.030 |

## Conclusions

In general, the hardness plays an important role in rock mechanics and excavation engineering. Hardness investigation with indentation mechanism is also important in selection of suitable cutting tools for mining and construction machinery. Therefore, the current study is focused on the effect of the textural characteristics on Vickers indentation hardness of 12 limestone samples. For this purpose, seven indicators were calculated and applied to describe the rock textural characteristics: equivalent diameter, compactness, shape factor, aspect ratio, interlocking index, grain size homogeneity, and texture coefficient. This study presents some results as follows:

- The Vickers hardness increases with increasing grain compactness, aspect ratio, grain size homogeneity, interlocking grain index, and texture coefficient. Therefore, it could clearly represent all mentioned parameters and could lead the engineers to make better decisions by a minimum amount of investigation
- Among the seven textura
- l characteristics, three parameters of grain size, texture coefficient, and aspect ratio have the greatest effect on Vickers hardness. Therefore, in the limestones by variable grain size and texture, the Vickers test should be carried carefully and with full consideration of the sample texture
- The results of the analyses show that the effect of grain size is greater in very fine-grained than in fine-grained limestones
- The statistical and regression analysis show that the Vickers hardness and grains' equivalent diameter are correlated more significantly than any other textural parameters

According to the experiences achieved during the laboratorial studies, in the continuation of the current paper, it is essential to study the effect of rock textural specifications on other indentation hardness testing methods such as Brinell, Knoop, and Rockwell. It is also recommended to simulate the effect of grain size of limestone samples on indentation hardness using numerical methods such as a discrete element method (DEM) and compare with the results of laboratory studies to get a better view of indentation mechanism.

## Declarations

**Competing interests** The authors declare no competing interests.

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