



# A review on rock hardness testing methods and their applications in rock engineering

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## Abstract

This paper aims to discuss the recent development in rock hardness testing methods and their applications in rock engineering and geological studies. Hardness is one of the essential physical characteristics of minerals and rocks, with dominant effects on rock mechanics and excavatability. In this paper, all available rock hardness testing methods are classified into main categories: static and dynamic methods. After that, standards and testing procedures have been briefly discussed using various literature. The review clarifies the dominant factors that affect the rock hardness as well as physicomachanical characteristics, which affect the hardness. The correlations between different hardness testing methods are analyzed using regression analysis, and their interconnections between them are presented. Also, the applications of hardness scales in the assessment of rock excavatability and machinability have been investigated. In total, it could be concluded that dynamic hardness testing methods have been widely applied in rock engineering. However, the relative standards and field measurement procedures have not been developed well. Future research must incredibly be focused on this lack of past studies and should try to develop reliable models for the prediction of physicomachanical rock parameters.

**Keywords** Hardness · Physicomachanical characteristics · Dynamic hardness methods · Regression analysis · Machinability

## Introduction

Determining the physical and mechanical characteristics is essential for the classification of rock materials and decision-making about their suitability for various mining and construction purposes (Yaşar and Erdoğan 2004). Understanding the physical properties of rocks is the fundamental part of the field and laboratory investigations of the rocks, which provides technical support for engineering analysis, such as excavation method selection. As ISRM (1981) recommends, “Site investigations, laboratory and field tests provide important inputs for rock modeling and rock engineering design approaches. Therefore, determination of rock properties both in the laboratory and in-situ monitoring of

rock behavior and rock structures provides important areas of interest in rock mechanics and rock engineering, which are commonly applied to engineering for civil, mining, and petroleum purposes.”

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. Due to the complexity of hardness from the engineering perspective, a unique and comprehensive definition has not been recommended for it. However, many narrow-vision definitions of rock and mineral hardness have been presented by different researchers from the viewpoint of different applications and mechanisms. Mohs stated that hardness is the mineral’s stability that shows against the particle’s displacement. Bloss (1994) notes that both the Mohs scale and indentation hardness method measures a mineral’s resistance to “mechanical breakdown.” Also, Klein (2002) points out: “The resistance that a smooth surface of a mineral offers to scratch is its hardness.” Perkins (2002) defined mineral hardness as: “Hardness is a mineral’s resistance to abrasion or scratching.” Jimeno et al. (1995) believe that rock hardness is the first resistance that must be overcome during the excavation process. Based on Verhoef’s

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idea (1997), hardness refers to a rock or mineral's resistance against a cutting tool. Hardness indicates the rock's resistance to penetration, scratch, or permanent deformation (Heiniö 1999; Demirdag et al. 2009; Winkler 2013). Generally, hardness means the resistance of a material to the penetration of another hard material (Gokhale 2010; Bell 2013). Hardness may also be referred to as mean contact pressure related to the plastic flow stress of materials (Herrmann 2011). Finally, it can be concluded that geoscience researchers have provided various definitions depending on the type of mechanism used in measuring hardness. The various mechanisms available in hardness testing methods will be detailed and reviewed in future sections.

Rock is composed of many minerals, and each mineral does have a specific value of hardness. Mineral hardness is related to other physical properties, such as cleavage, luster, and streak, commonly taught to geoscience researchers. This property is also a good example of a base discussion of links between crystal chemistry, crystal structure, bond types/strengths, and macroscopic properties (Whitney et al. 2007). Nevertheless, due to differences in the percentages of minerals, the same type of rocks' hardness differs within a specific range. Therefore, the value of hardness concerns a specific hardness scale (Gokhale 2010).

Hardness is in strong correlation with the rocks' mechanical characteristics and is a dominant factor in the workability of the rocks, which directly affects the excavation process and costs. Generally, rock hardness is responsible for the wear of tools, degradation of mining machines, the increment of the operational costs, and a significant reduction in operational efficiency (Thuro et al. 2006). Therefore, hardness has been a powerful motivation for developing any new rock excavation machinery, advanced mining tools, and high-tech tool manufacturing materials in recent decades.

This paper first provides a comprehensive overview of rock hardness testing methods and standards. Next, the parameters affecting rock hardness are discussed, and most of the proposed experimental correlations between hardness and other geomechanical rock parameters are presented in detail.

## Rock hardness testing methods

The rock hardness value depends not only on the tested material but also on the testing method. In general, the hardness is affected by the material structure, especially the atoms' bonding forces (Herrmann 2011). It is also influenced by the inherent factors such as minerals, grain size, boundary cohesion of minerals, strength, elastic, and plastic behaviors of rocks (Osanloo 1998). In general, hardness is a function of bonding strength (and therefore of crystal chemistry and structure), so it is a useful

property for understanding the relationship between the structure and composition of crystals and their macroscopic properties (Whitney et al. 2007).

Each available rock hardness testing method deals with one or a few mentioned rock material features to define and measure a specific hardness value. On the other hand, the testing mechanisms and procedures are widely different. Many rock hardness testing methods have been developed and applied in different rock engineering applications with various mechanisms and considering different rock characters. According to the literature survey in this paper, rock hardness testing methods are classified into different types considering the following tool–rock interaction mechanisms:

- Scratch
- Indentation
- Grinding
- Rebound

Scratch hardness is the ability of one solid to be scratched by another harder solid and is a complicated function of the elastic, plastic, and frictional properties of a mineral surface (Winkler 2013). Mohs hardness is one of the scratch-based methods which is widely applied in rock and mineral hardness testing. In the grinding hardness mechanism, sand or other abrasive granules impinge on the surface of the workpiece being tested under standard conditions, and the hardness value is measured based on the loss of material in a given time (Chandler 1999).

Indentation hardness is the permanent indentation of the mineral surface by a sphere, a cone, or a pyramidal indenter. The hardness is determined by the load and the size of the indentation (Winkler 2013). The indentation hardness tests are divided into three types: micro-indentation, macro-indentation, and nanoindentation tests. Micro-indentation tests are characterized by indentations loads in the range of  $F < 2$  N; with penetrations depths more than  $0.2 \mu\text{m}$ , macro-indentation tests are in the range of  $2 \text{ N} < F < 30 \text{ KN}$ ; and in the nanoindentation method, the maximum load ranges between few  $\mu\text{N}$  and about  $200 \text{ mN}$ , while penetrations will vary from few nm to about few  $\mu\text{m}$ . The Knoop hardness test method is one of the micro-indentation tests, and Rockwell and Brinell tests are in the macro-indentation class. The Vickers test is classified in both macro and micro classes based on the sample's applied load range. For  $F < 1 \text{ Kg}$  ( $\sim 9.8 \text{ N}$ ), the type of test is micro-indentation, and more than  $\sim 9.8 \text{ N}$  is placed in the macro-indentation category (Broitman 2017).

Rebound-based hardness methods measure the rebound of the diamond-tipped hammer dropped from a fixed height onto a rock surface. This type of hardness is related to [elasticity](#); thus, any plastic deformation reduces the elastic hammer energy (Hudson 1993).

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 hardness testing. In the static methods, the test force is gradually increased, and it is applied smoothly within a minimum time stipulated in the standards. In the dynamic methods, the test force is applied abruptly, and the test specimen is subjected to an impact load. According to the results of the vast literature survey by the authors, all well-known rock hardness testing methods could be classified, as shown in Fig. 1. A detailed discussion about each of the methods will be presented in the next parts of the paper.

### Rock hardness testing scopes and procedures

Different hardness testing methods are implemented based on various fundamentals and are different in logic, mechanism, volume, scale, and time. In the following sections, the hardness methods of rocks are briefly reviewed.

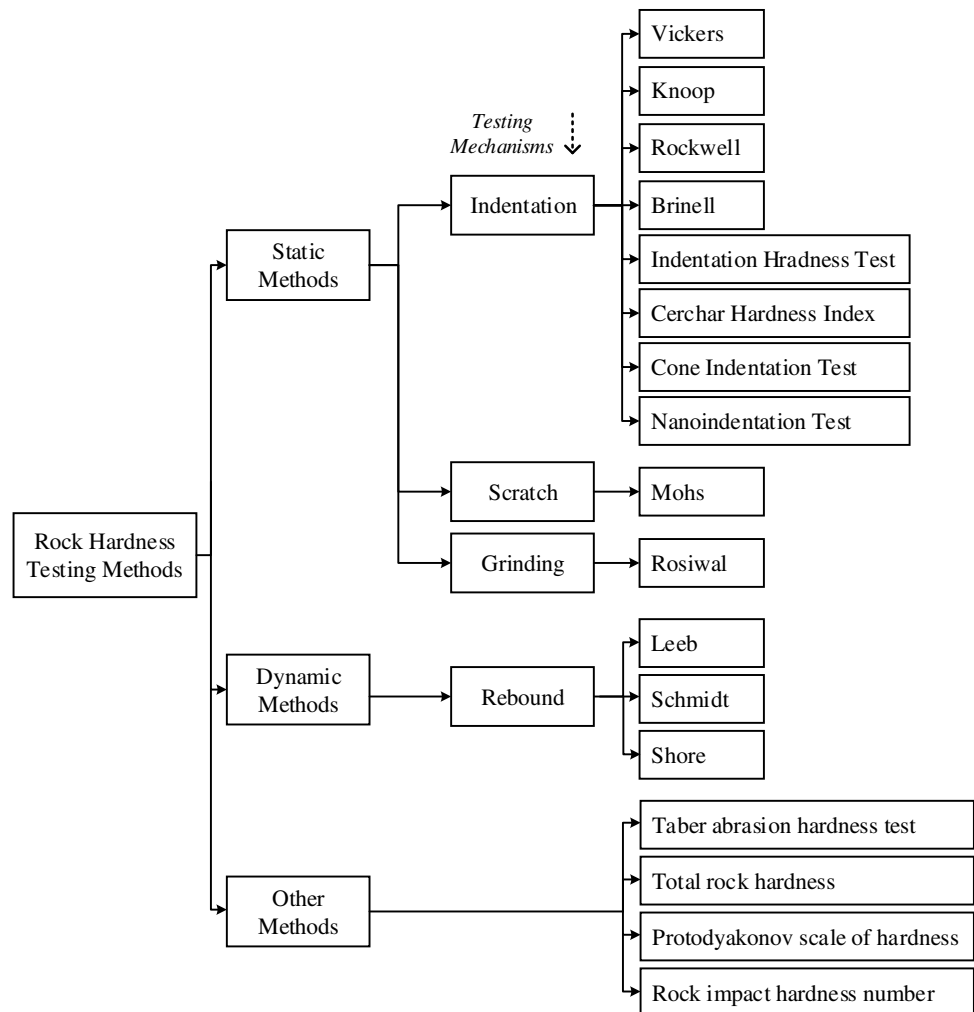
### Static hardness methods

#### Mohs scale hardness

Mohs hardness test as one of the most important, more precise, and basic minerals' hardness testing methods was introduced by Mohs. This test compares a mineral's 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 (see Fig. 2).

Mohs scale is an effective tool for identifying minerals and understanding the influence of crystal structure and chemistry on physical properties, e.g., hardness (Whitney et al. 2007). This scale is the most popular and applicable method for evaluating and classifying rock hardness because it is directly based on mineralogical studies and has an excellent ability to analyze rock hardness (Hoseinie et al. 2009, 2012). It is essential to know that the Mohs scale considers the different orientations of the crystals in minerals. This difference is due to the atomic

Fig. 1 A general classification of rock hardness testing methods based on literature review



**Fig. 2** Mohs scale of mineral hardness (<http://www.sierrapelona.com/glossary/mohs-hardness/>)



structure and different bonding characteristics in various minerals (Broz et al. 2006). Hence, for accurate determination of rock hardness with the  $n$  number of minerals, the percentage of every contained mineral in each section is specified. Based on the hardness of each recognized mineral, the rock hardness is calculated by Equation 1:

$$M.H = \sum_{i=1}^n A_i \times (M.H)_i \quad (1)$$

According to the above description, some minerals have different hardness in the longitudinal and transverse directions. Therefore, it is necessary to calculate the hardness for both longitudinal and transverse directions, and the average hardness of these two directions is considered the rock Mohs hardness.

### Vickers hardness

Vickers hardness is a hardness method that determines the material's hardness based on the material's strength against the square-based pyramidal diamond. This method was first introduced by Smith and Sandly (1922) as an alternative to the Brinell method. The standards of ISO 6507-1 (2018) and ASTM E92-16 (2016) are for the Vickers hardness test of metallic materials.

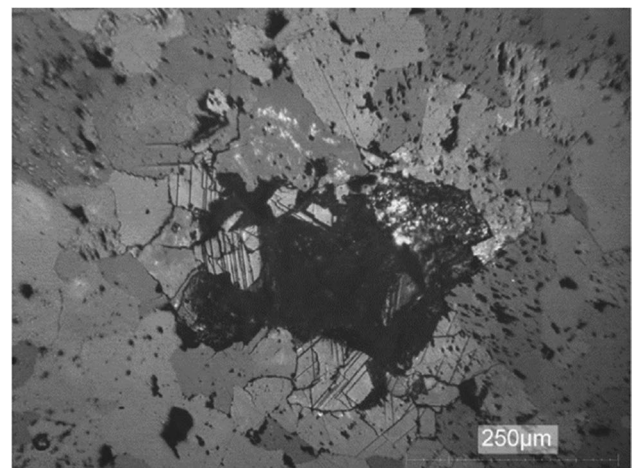
The rock is generally a non-homogeneous material and consists of several minerals of widely varying individual grain hardness. The Vickers hardness of rock or the "surface hardness" of the rock is an aggregate value based on its mineral constituents' weighted hardness values, which are calculated by Equation 2 (Heiniö 1999). To measure the Vickers hardness of rocks directly, an average of 3–5 points was quoted as a value of microhardness of a mineral forming the rock (Xie and Tamaki 2007; Aydin et al. 2013a):

$$V.H = \sum ((V.H)_j (\% \text{ mineral}_j / 100)) \quad [Kgf/mm^2] \quad (2)$$

It should be noted that the Vickers hardness on minerals is more problematic than on metals. In metals, the impression of the Vickers diamond is mainly permanent (plastic). In rocks and minerals, an essential part of the deformation during indentation is recoverable (elastic) (Verhoef 1997). Also, it is difficult to identify the indentation diagonal of various hard and brittle minerals in the experiment due to the fracture around the indentation (Xie and Tamaki 2007). An example of fracture networks into the neighboring grains in a crystalline rock due to Vickers tip indentation is shown in Fig. 3. As shown in Fig. 3, it is difficult to detect the real border of the residual square-shaped impression due to the tip penetration after removing the load.

### Brinell hardness

Brinell hardness is determined based on rocks' strength against the tungsten steel or tungsten carbide of the spherical indenter. This method was introduced by Brinell (1900). In the Brinell hardness test, an indenter (with diameters of 1,



**Fig. 3** An example of a micrograph of a Vickers indent by applying 20 N (Bandini et al. 2014)



2.5, 5, and 10 mm) is forced into the surface of a test piece for 10–15 s. After unloading, the diameter of the indentation is measured. The standards of ISO 6506-1 (2014) and ASTM E10-17 (2017) have been developed for the Brinell hardness test of metallic materials. The Brinell hardness of rock is measured in the same way as metals (Boutrid et al. 2015).

### Rockwell hardness

Rockwell is one of the hardness metal methods measured based on the strength against the indenter with different loads. This method was introduced in 1914 by the Stanley brothers (Rockwell and Rockwell 1914). In this method, the test specimen's surface is forced by the diamond indenter, and the initial indentation depth is measured. By maintaining the preliminary force, the main force is applied. After that, the main force is removed, and only the preliminary force remains. The final indentation depth is measured. The standards of ISO 6508-1 (2016) and ASTM E18-15 (2015) have been developed for the Rockwell hardness test of metallic materials.

Rockwell hardness test is easy to perform with excellent results for minerals and rocks because pre-loading of the specimen eliminates errors through elastic recovery (Winkler 2013). The Rockwell hardness test is similar to the Brinell method, but the difference between the two tests is the smaller load and the indenter shape in the Brinell test, in which the created indentation is smaller and more in-depth.

### Knoop hardness

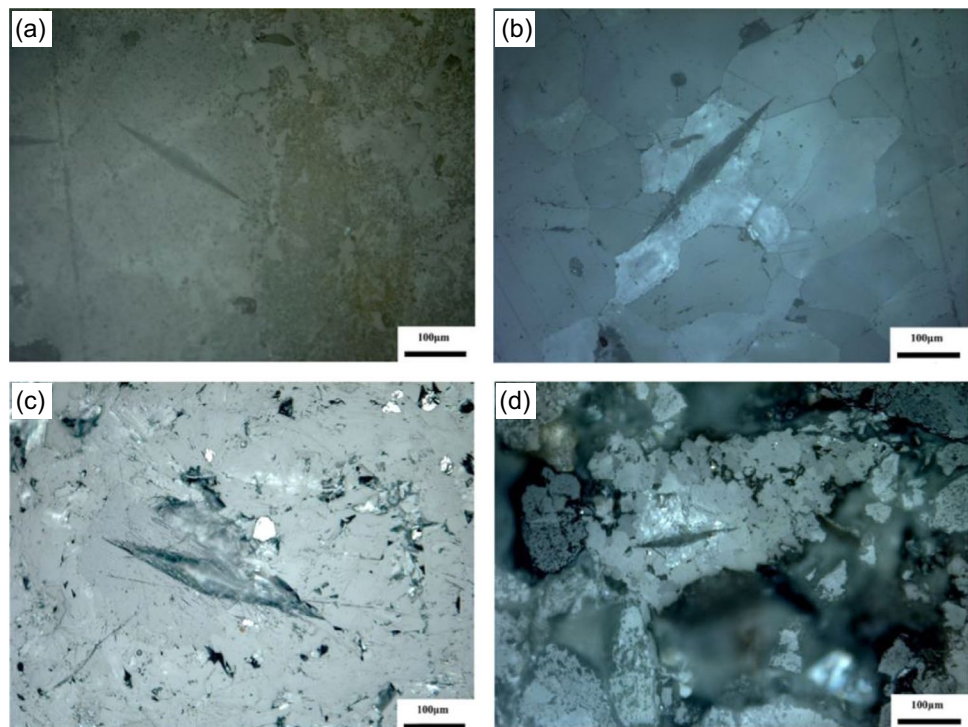
The Knoop hardness test was developed by Knoop et al. (1939) as an alternative to the Vickers test. The standards of ISO 4545-1 (2017) and ASTM E92-16 (2016) have been developed for the Knoop hardness test of metallic materials.

In this test, the test specimen's surface is forced by a rhombic-based, pyramidal diamond indenter. The diamond tip is placed on the sample's prepared surface, and it will be placed for 10–15 s under specific forces from 1 gf (0.009807 N) to 2 Kgf (19.61 N). Then, the mean Knoop indentation diagonal length ( $d_k = \frac{d_1+d_2}{2}$ ) is measured by a microscope after unloading. It is important to note that the imprints of indentation will vary depending on the type of rock and the amount of applied load. An example of the imprints of Knoop indentation in different rock samples is shown in Fig. 4.

There are three standards of TS EN 14205 (2004), BS EN 14205 (2003), and EVS-EN 14205 (2004) for measuring the Knoop hardness of natural stones. At least one polished section shall be prepared in the British standard (BS EN 14205 2003) approximately 20 mm in width, 30 mm in length, and 10 mm in thickness.

The important point about the four indentation methods, including Vickers, Knoop, Brinell, and Rockwell, is the limitation of their use in rock engineering. In other words, these four methods have been developed for metallic materials applications (Broitman 2017). But there are still no complete and codified standards except for the Knoop method

**Fig. 4** Images of imprints of Knoop indentation in different rock types **a** chalk, **b** limestone, **c** sandstone, **d** marble (Athanasidou et al. 2016)



that can be used in rock mechanics applications. Therefore, to use the mentioned methods in rock mechanics applications, the effect of different parameters and the correlation between them should be studied in detail. In other words, it is necessary to study various parameters of rock materials on a laboratory scale in a wide range of rocks to provide standards for the application of each method in rock engineering.

Examining the standards in each of the four methods, it can be seen that to use the Knoop, Vickers, Brinell, and Rockwell hardness methods in non-metallic materials, more laboratory studies should be performed on rock samples with different physical and mechanical properties. Some of the important parameters that should be considered in performing the hardness methods mentioned in rock materials are:

- Scale effect (thickness, area, and volume of rock sample)
- The shape of the rock sample (core, block, or irregular form)
- The pattern of hardness testing on the rock sample
- Number of hardness tests on surface of rock sample
- Effect of physical, mechanical, and textural properties of rock
- Effect of weathering of rock sample
- Temperature effect
- Surface roughness effect (surface finish)

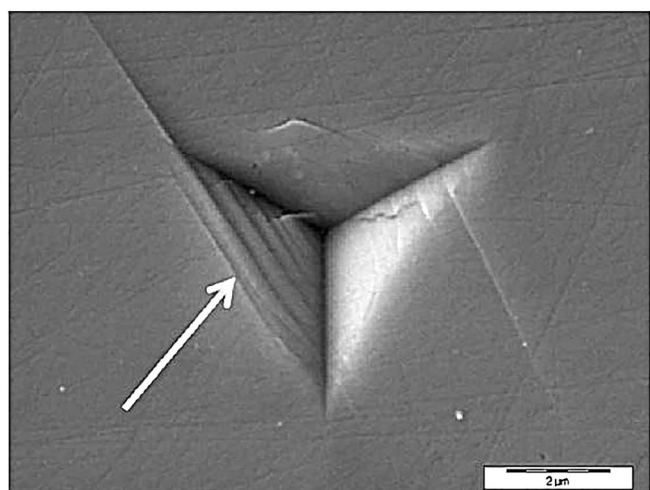
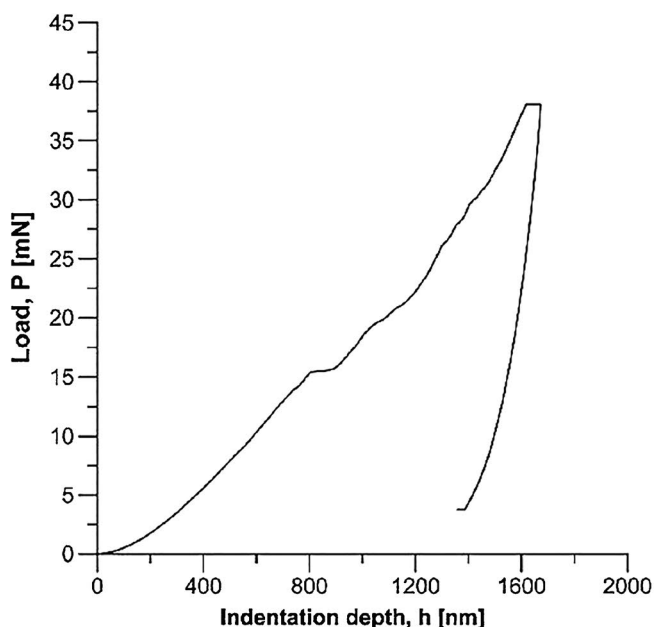
### Nanoindentation test

Nanoindentation has become an increasingly popular method to determine the mechanical properties of both homogeneous and heterogeneous materials (Ma et al.

2020). A single nanoindentation experiment involves loading the sample (by applying a user-specified force or specifying the depth of investigation into the sample) and subsequently unloading the sample (Shi et al. 2019). There are mainly two indenter shapes in nanoindentation: Berkovich and cube corner. The Berkovich indenter is a three-sided pyramid with a face angle of  $65.3^\circ$  concerning the vertical indentation axis, and its area-to-depth function is the same as that of a Vickers indenter (Berkovich 1951). The cube corner is also a three-sided pyramid which is precisely the corner of a cube (Broitman 2017).

The nanoindentation test can be carried out by the constant loading rate (CLR) or the constant loading strain rate (CSM) model. The theoretical basis for the CLR model was established by Oliver and Pharr (1992). There is a stage of elastic deformation when the nanoindenter starts to press on the rock surface. After that, the increasing load results in plastic deformation, and an eternal indent can be observed according to the geometry of indenters.

CSM depends on imposing fast oscillation with high frequency to the quasi-static loading signal; thus, a harmonic force can be added to the load. The main advantage of CSM is that it offers direct measurement of the dynamic contact stiffness,  $S$ , at any point along the loading curve (Shi et al. 2020). Figure 5 shows an example of the load–indentation curve of Berkovich nanoindentation and SEM micrograph, in CSM mode. It should be noted that the load–indentation curves are never regular and in the loading part often exhibit pop-in phenomena. Pop-in phenomena mean a sudden discrete increase of penetration



**Fig. 5** Load–indentation curve and SEM micrograph of a Berkovich indent (Bandini et al. 2012)

depth at an approximately constant load, due to the brittle failure induced by the indenter (Bandini et al. 2012).

**Cone indentation hardness**

The Cone indenter (standard) was designed at the Mining Research and Development Establishment (MRDE) of the previous National Coal Board (NCB) of the GB to test the resistance of the rock and coal against the indentation of a tungsten carbide cone by the angle of 60°. This method determines the hardness of small fragments of rocks by the dimensions of 12 × 12 × 6 mm. By considering displacement between the first and the second advancement (M1 and M2) and the deflection of the thin spring bond measured by the gauge, the standard cone indenter hardness is calculated using Equation 3 (Szlavin 1974; Bilgin et al. 2013):

$$CIH = \frac{0.635}{(M1 - M2) - 0.635} \tag{3}$$

One of the restrictions of this method is the small penetration depth in hard rocks. For this reason, in 1974, Szlavin modified this method. In the modified version, the applied indentation force was increased to 110 N (Szlavin 1974). One of the important points in Cone indentation hardness is that it does not give any good results in coarse grain rocks.

**Cerchar hardness index**

This test was developed at the Laboratoire du Center d’Etudes et Recherches des Charbonnages (CERCHAR) de France and published by Valantin (1974), which was primarily used to define the strength and cuttability properties of coal or rock samples (Yaralı 2017).

In this method, a bit of tungsten carbide with a diameter of 8 mm and an inclusive tip angle of 99° is rotated on the rock sample by a force of 200 N. The drilling time of a hole to a depth of 1 cm is considered the Cerchar hardness index, assuming constant rotation speed (Valantin 1974;

**Table 1** Cerchar hardness index scale (Sofretu and Schwenzfeier 2005)

CHI (s)	Descriptive terms
0–20	Soft rock
21–40	Moderately hard rock
41–80	Hard rock
81–120	Very hard rock
> 120	Extremely hard rock

Yaralı 2017). Table 1 presents the Cerchar hardness scale qualitatively.

**Indentation hardness index**

In this method, a rock sample with a height to diameter ratio of at least 0.75:1 is placed on the lower plate of the point load apparatus and is loaded. The conical platen has a 60° cone and a 5 mm radius spherical tip. The tip transmits the load to the specimen, and a dial gauge reads the resultant penetration zone. The indentation hardness value is obtained by dividing the maximum load (in KN) by the maximum penetration zone (in mm) according to Equation 4. The proposed classification of the rock hardness according to the indentation hardness index is shown in Table 2. The mean of at least three tests on the sample is reported as the indentation hardness value (Szwedzicki 1998; Kahraman and Gunaydin 2008). The indentation hardness index indicates the rock’s resistance to elastoplastic deformation (Hoseinie et al. 2012). More details on this method are provided by Szwedzicki (Szwedzicki 1998):

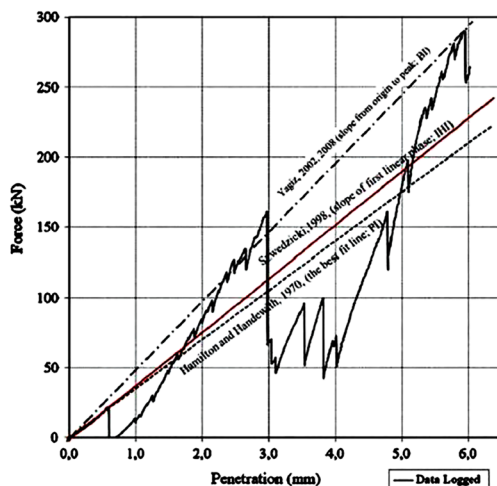
$$IHI = \frac{L}{p} \tag{4}$$

The rock indentation test has undergone many modifications and improvements since its initial introduction a few decades ago. The earlier interpretations involved drawing a best fit straight line on the force–penetration profile through the origin and directly estimating the expected cutter load and penetration during excavation (Handewith 1970; Hamilton and Handewith 1971). Szwedzicki (1998) proposed that the indentation hardness index could be computed from the first elastic or linear phase of the force–penetration curve as shown in Fig. 6.

**Table 2** Classification of rock hardness based on indentation testing (Szwedzicki 1998)

IHI	Classification of the rock
> 50	Extremely hard
40–50	Very hard
30–40	Hard
25–30	Moderately hard
20–25	Moderately soft
15–20	Soft
8–15	Very soft
< 8	Extremely soft

**Fig. 6** Various expressions from the force–penetration graph of the indentation test (Yagiz 2009a)



Three distinct phases from indentation test:

- first phase: Related to elastic deformation
- Second phase: Related to crushing of rock fabric
- Third phase: Marked by chip formation in the rock

Three parameters from indentation test:

- Penetration Index (PI), KN/mm or lb/in
- Indentation Hardness Index (IHI), KN/mm
- Brittleness Index (BI), KN/mm

### Rosiwal hardness

The Rosiwal hardness is regarded as a measure of the resistance of rock or mineral against abrasive wear. This scale is based on the reaction of minerals against a standard abrasive powder (Corundum powder or, in some cases, dolomite or quartz powder, the workability of which was calibrated against corundum powder), which was used in meager quantities during the early experiments of this test. The test samples of 400 mm<sup>2</sup> are pressed by hand against a rotating metal or glass disc until the powder loses its workability. Later, a grinding time of 8 min was taken as standard, and the amount of corundum powder was specified at 100 mg (Verhoef 1997; Fowell and Abu Bakar 2007). In other words, the samples are ground to constant weight using a standard amount of abrasive powder until the powder is worn out.

The weight loss of the sample is a measure of its abrasive hardness (Broekmans 2007). In this scale, a value of 1000 is assigned to corundum, and the hardness of other minerals is measured as a ratio to it (West 1981). A diagram comparing the Mohs scale of hardness to the Rosiwal hardness (absolute hardness) is shown in Fig. 7. As with the Mohs and Vickers methods, it is possible to obtain an overall Rosiwal hardness using thin sections of rocks and their constituents' mineralogical descriptions according to Equation 5 (Yılmaz 2011):

$$Ro.H = \sum_{i=1}^n A_i \times (Ro.H)_i \tag{5}$$

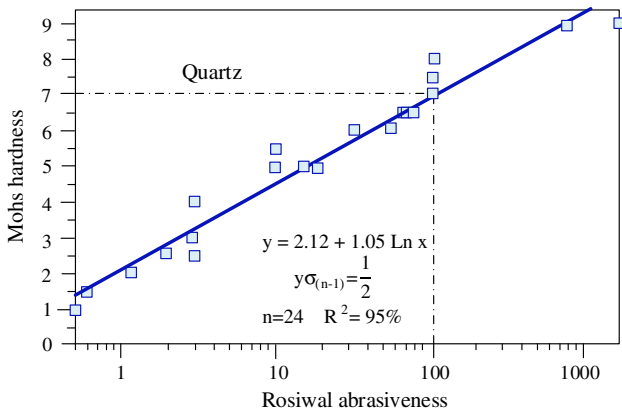
Widely used geotechnical wear indices such as abrasive mineral content (AMC), also referred to as “mean hardness,” are based on the Mohs hardness scale, the equivalent quartz

## Mineral Hardness Scale



**Fig. 7** Mineral hardness diagram (<https://artsandculture.google.com/asset/mineral-hardness-diagram/ngFqrlgEPLtKng>)





**Fig. 8** Correlation between Rosiwal abrasiveness and Mohs hardness, enclosing 24 different minerals (excluding diamond) (re-plotted with the data in (Thuro and Plinninger 2003))

content (EQC), which uses Rosiwal grinding hardness, and the Vickers hardness (Plinninger 2010).

The Rosiwal abrasiveness value of rocks could also be calculated by Mohs hardness using the relationship shown in Fig. 8. When the Mohs hardness is known, the abrasiveness of minerals can be estimated by this chart with satisfactory accuracy (within a half degree of Mohs hardness) (Thuro and Plinninger 2003).

### Dynamic hardness methods

#### Leeb or Equotip hardness test

An impact is transferred from a diamond or tungsten carbide ball to the rock specimen’s surface in the Leeb method. Leeb hardness number is calculated by dividing the rebound velocity by the velocity of the impact velocity as given in Equation 6 based on the ASTM A956-06

(2006). The schematic of the Leeb hardness test method is shown in Fig. 9.

$$L.H = \frac{\text{Rebound velocity}}{\text{Impact velocity}} \times 1000 \tag{6}$$

There are six types of impact devices used in Leeb hardness testing, including D, S, E, DL, D + 15, G, and C. Since the impact body is forced perpendicularly to the specimen surface, correction values should be used for other directions in different types of impact body. Based on the ASTM A956-06 (2006), three essential points that should be considered in Leeb hardness testing are as follows:

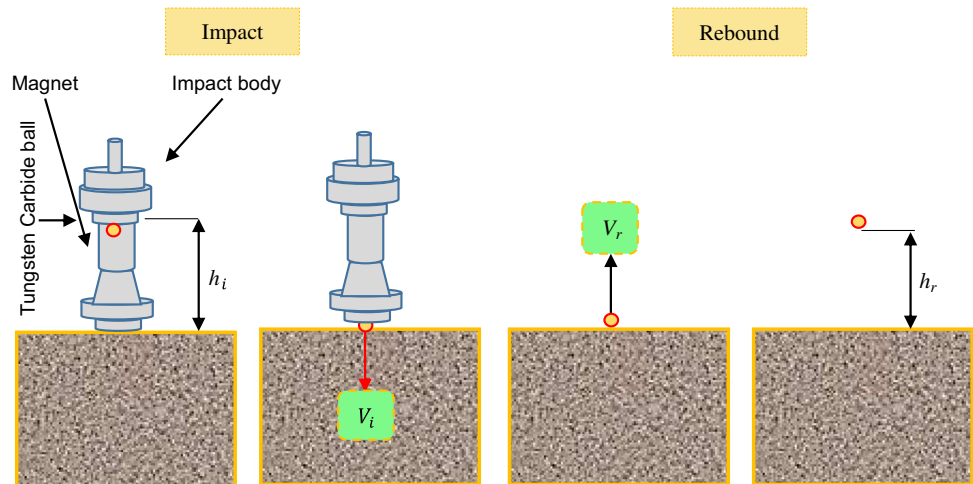
- The surface of the specimen must be carefully prepared to avoid the alteration in hardness.
- The magnetic fields affect the results of this test. It is recommended that any residual magnetic field be less than 4G.
- The sample should not be placed under vibration to perform the test correctly.

The D-type Leeb tester’s impact energy is approximately 1/200 of the Schmidt hammer N-type, and 1/66 of the Schmidt hammer L-type. Therefore, it causes less damage to the tested surface, and it provides significant results in soft and weak rocks. Also, the Schmidt hammer and Equotip hardness tester are both easily applied in the field and allow many readings to be collected over relatively large areas in quite a short period (Moses et al. 2014).

#### Shore hardness

The Shore hardness test has been accepted as a convenient and non-destructive method for measuring rock hardness

**Fig. 9** The principal of the Leeb rebound test



and is widely used in rock mechanics (Altindag and Güney 2006). This device is presented in two models: C and D.

The Shore hardness instrument has a small diamond-tipped hammer and a plastic bubble. The hammer drops freely from a fixed height onto a test surface. Then, the hammer rebound height is indicative of the hardness of the rock sample. It is measured on the calibrated scale, which gives the Shore hardness value in its units, ranging from 0 to 140.

Researchers have applied standard specimen dimensions to optimize the test results in the laboratory. Misra (1972) has reported that rock specimens with a diameter of 25 mm, a surface area of 4.91 cm<sup>2</sup>, and a length of 5 cm produced consistent Shore hardness values. According to ISRM (1978), the minimum value of the sample surface and the minimum thickness are proposed to be 10 cm<sup>2</sup> and 1 cm, respectively. Later, Rabia and Brook (1979) determined that the minimal specimen volume is 40 cm<sup>3</sup>. Holmgeirsdotir and Thomas (1998) have investigated the effect of the D-type of Shore scleroscope instrument for testing small rock volume. Their results show that not only is D-type more easily read than C-type but that it is capable of being applied to small test specimens. Altindag and Güney (2006) in an experimental study proposed the critical volume of rock samples of 80 cm<sup>3</sup>.

### Schmidt hammer hardness

The Schmidt hammer hardness test was initially developed to measure in situ non-destructive surface hardness of concrete (Schmidt 1951). Nevertheless, it has been widely used for rock engineering applications too. The hammer's plunger is placed on the specimen and is pressed into the hammer by pushing the hammer on the specimen. Energy is stored in a spring that automatically releases at a prescribed energy level and impacts a mass under the plunger. The mass's rebound height is measured on a ruler scale and is recorded as the measure of hardness (ISRM 1978).

Two types of Schmidt hardness are used in rocks: type L and N. The N-type hammer is less sensitive to surface irregularities and is preferred for field applications, while the L-type hammer has higher sensitivity in the lower range and gives better results in weak, porous, and weathered rocks. Also, the "L" type's impact value is three times less than the "N" type (0.735 Nm compared to 2.207 Nm) (Demirdag et al. 2009).

As Shore method, many research efforts have been made to provide a standard specimen size for the Schmidt hardness test. The proposed block edge length based on ISRM (1981) and ASTM D5873-14 (2005) is 6 cm and 15 cm, respectively. Also, Aydin (2008) and Demirdag et al. (2009) suggested that the rock sample's edge dimensions should be 10 cm and 11 cm, respectively.

In general, it can be said that hardness testing methods with the rebound mechanism can provide fast, non-destructive, quantitative, and high-resolution measurements of rock mechanical properties that compare favorably with traditional laboratory tests (Lee et al. 2014, 2016; Yang et al. 2015; Liu et al. 2020). In other words, non-destructive tools such as dynamic hardness methods capable of measuring the geomechanical properties of construction materials through time are of considerable value in engineering (Coombes et al. 2013).

One of the important applications of Shore scleroscope and Schmidt hammer hardness is in determining the plasticity of rock samples. For this purpose, McFeat-Smith (1977) introduced the plasticity index (PI) using the Shore hardness method. It has been stated that after repetitive impacts, a plastically deformed surface was formed as a result of work hardening (Yasar 2020). Additionally, McFeat-Smith (1977) used the plasticity index along with cone indenter hardness to estimate the specific energy in rock cutting. The plasticity index is also calculated by Schmidt hammer hardness as given in Equation 7 (Yasar 2020). Higher PI means higher plasticity of the rock samples:

$$PI = \frac{Q_2 - Q_1}{Q_1} \times 100\% \quad (7)$$

where  $Q_2$  is the 20th rebound number and  $Q_1$  is the first rebound number.

### Other hardness methods

In addition to the methods and mechanisms classified and presented in the previous sections, researchers have also proposed other methods. Due to these methods' applications, although less than other methods in rock engineering, these methods have been studied and reviewed.

#### Taber abrasion hardness test

To determine the Taber abrasion hardness, each side of 2 NX size disks [1/4 inch (0.6 cm) thick] is revolved 400 times under an abrading wheel forced against the disc by a 250 g weight. Then, the weight loss of rocks is measured, and their average is calculated. Finally, the Taber hardness is calculated according to Equation 8 (Tarkoy 1973b, a). In other words, The Taber abrasion value is inverse weight loss. It is also important to note that this test is sensitive to factors that influence small-scale strength, shearing, crushing, and abrasion (Tarkoy 1973b):

$$H_A = \frac{1}{\text{Average wt. loss (gms)}} \quad (8)$$

### Total rock hardness

“Total” hardness was developed from the combination of the Schmidt rebound and Taber abrasion hardness methods which is presented by Tarkoy (1973a). This hardness test is calculated by Equation 9. This method was developed to predict the rock performance for estimates of boring progress such as the advance rate of TBM:

$$H_T = S.H.H \times \sqrt{H_A} \quad (9)$$

### Protodyakonov scale of hardness

Another scale of hardness is called the Protodyakonov scale (Jun et al. 2003), which has been less used by researchers in rock engineering than the other methods mentioned. This scale represents the relative value of rock resistance to failure ( $f = \frac{R}{10}$ ). According to the Protodyakonov scale of hardness, rock’s hardness is divided into five grades, as shown in Table 3.

### Rock impact hardness number

Rock impact hardness number (RIHN) was proposed by Brook and Misra (1970), as a modification of the Protodyakonov index. Cores with 25 mm diameter and 50 mm length were prepared from the rock in the earlier suggested method. The cores were air-dried and then weighed. Each specimen was placed in the mortar with the cylindrical axis horizontal and broken by some blows by a steel drop weight of 2.4 Kg. The fines below 500  $\mu\text{m}$  were weighed, and the percentage of fines by mass relative to the specimen mass was calculated. This procedure was repeated at different numbers of blows until the percentage of fines produced by a test was over 30%. A graph of the percentage of fines (y-axis) is prepared against the number of blows (x-axis). Finally, the “rock impact hardness number” was defined as the number of blows to produce 25% fines. Brook and Misra (1970) suggested that only one determination for each selected number of blows and four to five same rock types was adequate to determine RIHN.

Finally, a brief description of the standards and equations for each rock hardness testing method is presented in Fig. 10.

**Table 3** The hardness grades of rock (Zhang et al. 2017a)

Hardness grade	Very hard	Hard	Half-hard	Soft	Very soft
$f$	> 20	16–20	8–16	2–8	< 2

## Application of dynamic hardness testing methods in the prediction of characteristics of rocks

In this paper, the statistical and regression analyses have been done beyond the qualitative literature review based on the available data in past publications to recognize and synchronize the different ideas about rock hardness and its interaction with mechanical properties. For this purpose, simple linear and non-linear regression analyses were carried out by IBM SPSS statistical software version 22.0 (SPSS Inc.).

### Data processing

#### Data disintegration


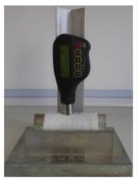








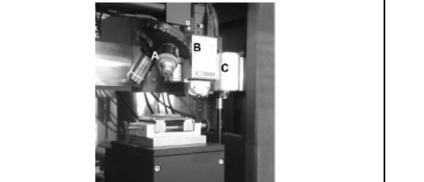
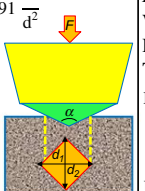
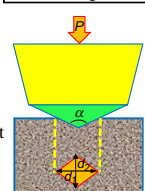
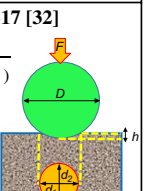
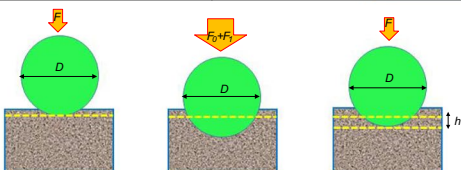
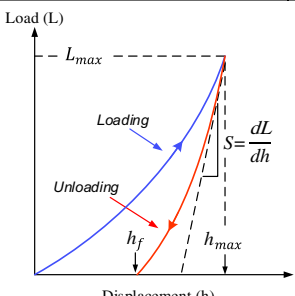
So far, many researchers have tried to estimate rocks’ mechanical characteristics using the rock hardness scales. The samples of different rock types used by various researchers in the previous studies were disintegrated based on origin. In other words, the database was subdivided into subsets by rock origin: sedimentary and igneous. It should be mentioned that due to the small number of metamorphic samples compared to igneous and sedimentary samples in previous studies, in this study, igneous and sedimentary samples have been analyzed. Additionally, in extracting the data and analyzing them, only studies dealing with the relationship between geomechanical parameters and rock hardness methods have been selected. Metamorphic rock types such as conglomerate, phyllite, chlorite schist, and serpentinite have not been well studied in previous studies. These rocks are very difficult to prepare samples and test in the laboratory or field due to the presence of structural anisotropy.

#### Data integration and regression analysis to predict UCS, Young’s modulus, and $V_p$ from dynamic hardness tests

In this section, all the origin grouped after data disintegration has been analyzed. For this purpose, the uniaxial compressive strength property has been investigated using dynamic hardness methods. Estimating the UCS using rock hardness tests is examined as a fast and preliminary method when physical and mechanical results are unavailable. In this paper, considering the large sets of available data in surveyed literature, the regression analysis was carried out on the database separately on each of the subsets to determine some correlations between UCS with Schmidt, Shore, and Leeb hardness scales in sedimentary and igneous rock samples.

Before determining the empirical formulas, the data set of UCS and L-type and N-type Schmidt hardness should be collected. In this paper, the data sets were collected from 26

**Fig. 10** Summary of standards and calculation of rock hardness values

						
1: Shore (S.H)	2: Leeb (L.H)	3: Schmidt (S.H.H)	4: Vickers (V.H)	5: Knoop (K.H)	6: Brinell (B.H)	7: Rockwell (R.H)
						
8: Indentation hardness (IHI)	9: NCB cone (CIH)	10: Cerchar hardness index (CHI)	11: Nano-indentation test			
<b>Standards, suggested methods, and testing procedures</b>						
<b>1 Altindag and Güney [67]</b> Block samples $V_c = 80\text{cm}^3$ ; $A_{\min} = 10\text{cm}^2$ $t_c = 8\text{cm}$ $S.H = \frac{\sum (S.H_1 + S.H_2 + \dots + S.H_{20})}{20}$		<b>2 Corkum et al. [216]</b> Block samples: $V < 90\text{cm}^3$ Core samples: $L/D > 0.4$ $L.H = \frac{\sum (L.H_1 + L.H_2 + \dots + L.H_{12})}{12}$		<b>3 Aydin [74]</b> Block samples: $t = 10\text{cm}$ Core samples: $\begin{cases} \text{L-type} \rightarrow \text{NX-size (54.7mm)} \\ \text{N-type} \rightarrow \text{T2-size (84mm)} \end{cases}$ $S.H.H = \frac{\sum (S.H.H_1 + S.H.H_2 + \dots + S.H.H_{20})}{20} \times CF$ $CF = \frac{\text{specified standard value of the anvil}}{\text{average of ten readings on the anvil}}$		
<b>4 ASTM E92-16 [26]</b> $V.H \text{ (MPa)} = 0.1891 \frac{F}{d^2}$ $d = \frac{d_1 + d_2}{2}$ 		<b>5 BS EN 14205 [40]</b> Rock samples: Width: 20 mm Length: 30 mm Thickness: 10 mm $K.H \text{ (MPa)} = 14.23 \frac{P}{L^2}$ L (mm): The length of the largest diagonal of the indentation P (N): The load on the indenter 		<b>6 ASTM E10-17 [32]</b> $B.H = \frac{2F_{kgf}}{\pi D(D - \sqrt{D^2 - d^2})}$ $d = \frac{d_1 + d_2 + \dots + d_n}{n}$ D: Ball diameter d: Indentation diameter 		
<b>7 ASTM E18-15 [36]; ISO 6508-1 [35]</b> $R.H = N - \frac{h}{S}$ S: Scaling constant N: Full range constant 						
<b>8 Szwedzicki [55]</b> Rock samples: $L/D = 0.75:1$ $IHI = \frac{L \text{ (KN)}}{P \text{ (mm)}}$		<b>9 Szlavin [50]</b> Small fragments of Rocks: $12 \times 12 \times 6 \text{ mm}$ $CIH = \frac{0.635}{(M1 - M2) - 0.635}$		<b>10 Valantin [51]</b> $CHI = \text{The drilling time of a hole to a depth of 1 cm by a force of 200 N}$		
<b>11 Retrieved from Oliver and Pharr [46]</b>		 <p>Nanoindentation hardness calculation:  <math>H = \frac{L_{max}}{A_c}</math>  <math>A_c = 24.56 h_c^2</math>  <math>h_c = h_{max} - 0.75 \times \frac{L_{max}}{S}</math>  <math>S = \frac{dL}{dh} \Big _{h = h_{max}}</math></p>				

references, and the basic information contained in the data sets is listed in Table 4. Because two types of the Schmidt hammer exist, to avoid the influence of the Schmidt hammer type, the collected data were divided into two parts: the

data determined by the L-type and N-type Schmidt hammer. Additionally, in addition, datasets of different rock properties and different hardness testing methods are divided into two main origins, igneous and sedimentary. Also, the



**Table 4** The basic information of the collected data sets (UCS Schmidt hardness)

Data source	Rock types	Schmidt hammer type
Sheorey (1984)	Coal samples	N-type
Kahraman (2001)	Dolomite, sandstone, limestone, marl, diabase, serpentine, hematite, metasandstone, tuff	N-type
Yaşar and Erdoğan (2004)	Limestone, marble, sandstone, basalt	L-type
Fener et al. (2005)	Basalt, granite, andesite, metagabbro, granodiorite, limestone, travertine	N-type
Buyuksagis and Goktan (2007)	Granite, marble, limestone, breccia, travertine	N-type and L-type
Kılıç and Teymen (2008)	Diorite, quartzite, limestone, sandstone, granodiorite, basalt, marble, trachyte, travertine, andesite, tuff	N-type
Çobanoğlu and Çelik (2008)	Sandstone, limestone, cement mortar	L-type
Dinçer et al. (2008)	Caliche samples	N-type
Kayabali and Selcuk (2010)	Gypsum, sandstone, andesite, ignimbrite, tuff, marble, limestone	N-type
Tandon and Gupta (2013)	Quartzite, granitoid, gneiss, metabasic, dolomite	N-type
Nazir et al. (2013)	Limestone	L-type
Karaman and Kesimal (2015b)	Basalt, dacite, limestone, volcanic breccia, basalt + dacite, andesite, biomicritic limestone	L-type
Yasar and Yilmaz (2015)	Dolomitic limestone, travertine, fossilized sandstone, lithic tuff, bioclastic limestone, granite, vitric tuff	L-type
Yilmaz et al. (2016)	Andesite, basalt, andesitic tuff, travertine, micritic limestone, marble, lithic tuff, diabase, dacitic tuff, gabbro	L-type
Armaghani et al. (2016)	Granite	L-type
Jamshidi et al. (2016)	Travertine	N-type
Azimian (2017)	Limestone	L-type
Hebib et al. (2017)	Limestone, sandstone, dolomite, calcareous tuff	L-type
Akram et al. (2017)	Limestone	L-type
Karakul (2017)	Ignimbrite, argillaceous limestone, andesite, sandstone, tuff, mudstone, marl, claystone	L-type
Jobli et al. (2017)	Granite	L-type
Demirdag et al. (2018)	Lymra, travertine, andesite, basalt, diabase, granite, obsidian, trachyte	L-type
Jamshidi et al. (2018a)	Sandstone	N-type
Yilmaz and Goktan (2019)	Basalt, micritic limestone, andesite, andesitic tuff, dacitic lithic tuff, lithic tuff, travertine, basalt, marble	L-type
Çelik and Çobanoğlu (2019)	Travertine, limestone, dolomite, granite, syenite, andesite, gabbro, dunite, tuff, ignimbrite	L-type
Ajalloeian et al. (2020)	Syenogranite, granodiorite, monzogranite, granite	N-type

sufficiently large size of the dataset guarantees the effectiveness of the empirical formulas.

In the next step, based on the collected database, we have tried to provide the characteristic regression equations for the prediction of UCS from L-type and N-type Schmidt hardness in sedimentary and igneous rock samples. As shown in Fig. 11, the UCS sedimentary and igneous of rock samples can be determined using L-type and N-type Schmidt hardness with reasonable  $R^2$  values. Also, as the database samples are large, it has a greater influence on the proposed trend line.

Table 5 shows the information about the statistics of the used data sources (UCS with Leeb and Shore hardness testing methods) that were used to develop the regression equations. Based on the regression analyses, a power regression equation was proposed to predict the UCS from

Shore hardness with a good  $R^2$  value of 0.72. Out of 11 previous studies, databases were used for sedimentary rock types. Also, only the 8 databases could be found to propose an exponential regression equation with a good  $R^2$  value of 0.74 in igneous rock types (Fig. 12).

The plot of the Leeb dynamic hardness as a function of UCS is shown in Fig. 13. There is a power relation with the weakest  $R^2$  of 0.63 between them in sedimentary rock types. Additionally, in igneous rock samples, a characteristic exponential regression equation was found with an excellent  $R^2$  value of 0.80. A total of 12 previous studies databases were used to suggest the regression equations for the prediction of the UCS from Leeb dynamic hardness in sedimentary and igneous rock types.

As can be seen in the figures, there are increasing trends in UCS of rocks with increasing hardness values. It seems

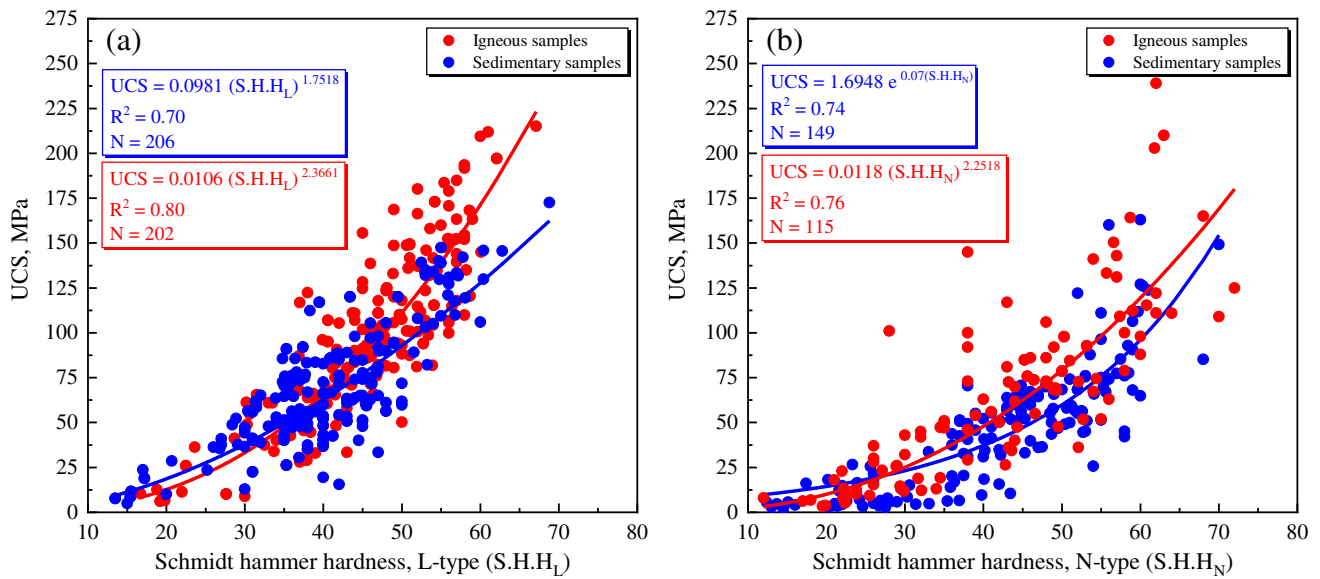


Fig. 11 Regression analyses between UCS and a L-type Schmidt hardness and b N-type Schmidt hardness

Table 5 The basic information of the collected data sets (UCS with Leeb and Shore hardness methods)

Parameters	Data source	Rock types	
UCS-S.H	Bell and Lindsay (1999)	Sandstone	
	Yaşar and Erdoğan (2004)	Limestone, marble, sandstone, basalt	
	Shalabi et al. (2007)	Shale, dolomite, dolomitic marble, diopside, anhydrite	
	Tumac et al. (2007)	Tuff, trona, chromite, copper ore, siltstone, limestone, sandstone	
	Kılıç and Teymen (2008)	Diorite, quartzite, limestone, sandstone, granodiorite, basalt, marble, trachyte, travertine, andesite, tuff	
	Dinçer et al. (2008)	Caliche samples	
	Çobanoğlu and Çelik (2017a)	Limestone, travertine, dolomite, granite, marble, andesite, latite, briquette	
	Závacký et al. (2017)	Granodiorite, trachyte, sandy marlite, limestone, sandstone, tuffite, shale	
	Çelik and Çobanoğlu (2019)	Travertine, limestone, dolomite, granite, syenite, andesite, gabbro, dunite, tuff, ignimbrite	
	Teymen and Mengüç (2020)	Andesite, aplite, aragonite, basalt, breccia, claystone, Dacite, diabase, diorite, dunite, gabbro, granite, granodiorite, gypsum, ignimbrite, limestone, lymra, microdiorite, onyx, quartz diorite, radiolarite, rhyolite, sandstone, shale, siltstone, spilite, syenite, trachyte, travertine, tuff	
	Holmgeirsdottir and Thomas (1998)	Slaty mudstone, greywacke, coral limestone, marble, sandstone, basalt, dolerite, microgranite, granodiorite	
	UCS-L.H	Verwaal and Mulder (1993)	Gypsum, calcarenite, dolomite, sandstone, limestone, marble, granite
		Hack et al. (1993)	Sandstone, granite, limestone
Asef (1995)		Gypsum, marl, breccia, conglomerate, sandstone, granodiorite, mudstone	
Meulenkamp and Grima (1999)		Mudstone, sandstone, limestone, granite, granodiorite	
Kawasaki et al. (2002)		Shale, sandstone, granite	
Aoki and Matsukura (2008)		Granite, gabbro, sandstone, andesite, tuff, limestone, laminate shale	
Yılmaz and Goktan (2018)		Basalt, limestone, micritic limestone, andesite, dacitic tuff, andesitic tuff, dacitic lithic tuff, agglomerate, travertine, marble	
Yılmaz and Goktan (2019)		Basalt, micritic limestone, andesite, andesitic tuff, dacitic lithic tuff, travertine, basalt, marble	
Çelik and Çobanoğlu (2019)		Travertine, limestone, dolomite, granite, syenite, andesite, gabbro, dunite, tuff, ignimbrite	
Yüksək (2019)		Tuff, basalt (volcanic rocks)	
Gomez-Heras et al. (2020)		Calcarenite, dolomite, limestone, marble, sandstone, tuff, granite, gabbro, andesite, dolostone, ignimbrite, travertine	
İnce and Bozdağ (2021)		Granite, tuff, basalt, andesite, phonolitic basanite, dacite, quartz andesite	

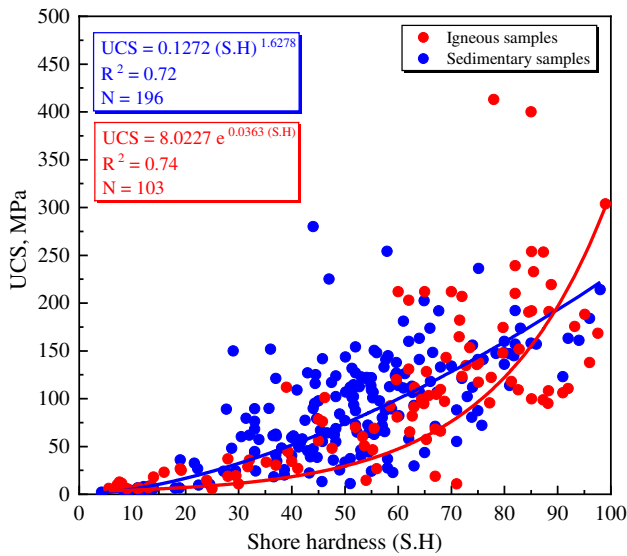


Fig. 12 Regression analysis between Shore hardness and UCS of rocks

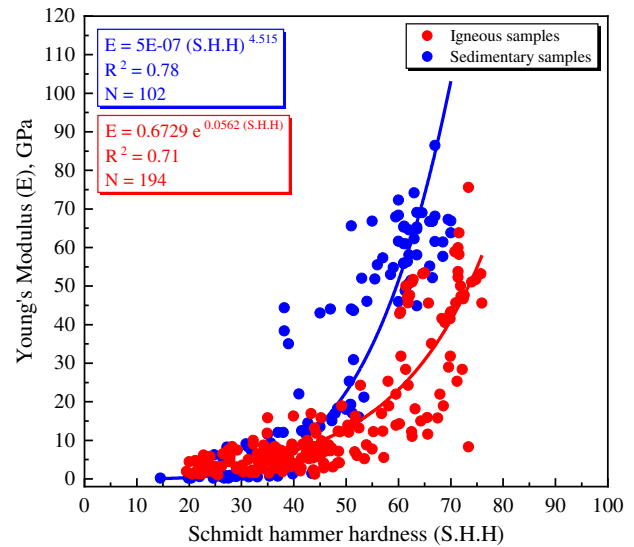


Fig. 14 Regression analysis between Schmidt hammer hardness and Young's modulus of rocks

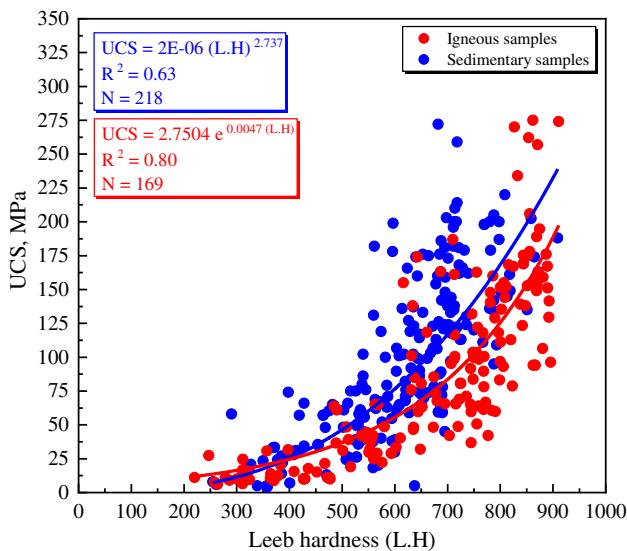


Fig. 13 Regression analysis between Leeb hardness and UCS of rocks

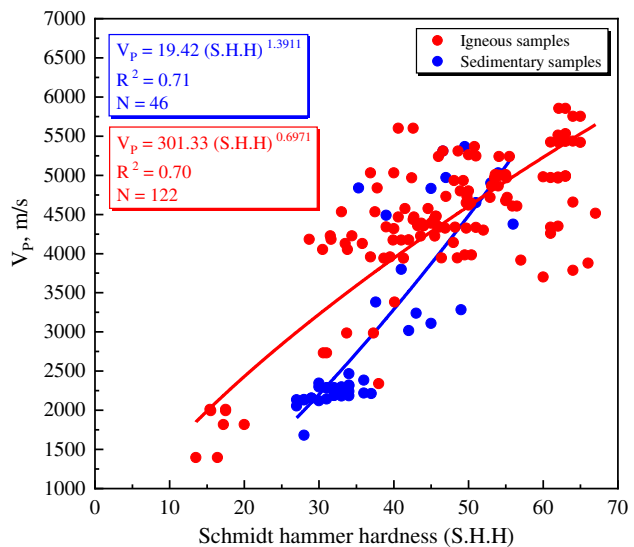


Fig. 15 Regression analysis between Schmidt hammer hardness and Vp of rocks

that Leeb's hardness establishes the best correlation with the UCS in comparison with other scales in igneous rock samples. In other words, the high coefficients of determination of the presently established prediction models suggest that the Leeb dynamic hardness method can be used for preliminary estimations of the UCS of similar fresh rocks with reasonable accuracy in igneous samples.

Further analysis has been investigated to correlate the Schmidt hardness with Young's modulus (E) and Vp (Figs 14 and 15). Table 6 shows the information about the statistics of the used data sources (Schmidt hardness with Young's modulus and Vp) that were used to develop the regression

equations. Figure 14 shows that sedimentary rock types have specific correlations and trends with Young's modulus, and there are reasonable equations to estimate Young's modulus by applying the Schmidt hammer hardness in both igneous and sedimentary samples. A total of 8 previous studies databases were used to suggest a characteristic regression equation for the prediction of Young's modulus from Schmidt rebound hardness. Additionally, as shown in Fig. 15, the P wave velocity increased with increasing Schmidt hardness in both sedimentary and igneous samples. However, these relationships showed reasonable increasing trends with the

**Table 6** The basic information of the collected data sets (E and  $V_p$  with different hardness testing methods)

Parameters	Data source	Rock types	Additional information	
E-S.H.H	Aggistalis et al. (1996)	Gabbro, basalt	Not given hammer type	
	Katz et al. (2000)	Chalk, limestone, marble, syenite, granite	N-type	
	Diñçer et al. (2004)	Andesite, basalt, tuff	Not given hammer type	
	Aydin and Basu (2005)	Granite	L-type and N-type	
	Vasconcelos et al. (2007)	Granite	N-type	
	Diñçer et al. (2008)	Caliche samples	N-type	
	Yagiz (2009b)	Travertine, limestone	Not given hammer type	
	Briševac et al. (2017)	Mudstone, grainstone, floatstone, wackestone, packstone	Not given hammer type	
	V <sub>p</sub> -S.H.H	Gupta (2009)	Granite, gneiss, quartzite, marble	N-type
		Yagiz (2009b)	Travertine, limestone	Not given hammer type
Sharma et al. (2011)		Sandstone, siltstone, conglomerate, granite, basalt, andesite	N-type	
Khandelwal (2013)		Quartzite, granite, dolomite, sandstone, limestone, shale, kota stone	N-type	
Sousa (2014)		Granite	AT-241/E tester	
Karaman and Kesimal (2015a)		Basalt, dacite, limestone, volcanic breccia, basalt + dacite, andesite, biomicritic limestone	L-type	

good  $R^2$ . Only the 6 references have been used to suggest these relationships.

In addition to Schmidt hardness, other hardness testing methods were also commonly applied to evaluate the physico-mechanical properties of rocks. Many attempts have been made to predict the correlation between physico-mechanical properties with dynamic and indentation hardness testing methods. To summarize, the research methods can be classified and reviewed in Table 7.

$E$ , Young's modulus;  $\gamma$ , unit weight;  $BTS$ , Brazilian tensile strength;  $n$ , porosity;  $w$ , water absorption;  $S.H.H$ , Schmidt hammer hardness;  $S.H$ , shore hardness;  $B.H$ , Brinell hardness;  $V.H$ , Vickers hardness;  $IHI$ , indentation hardness index

### Validation of the regression analyses

In this paper, the simple bivariate regression analyses have been performed, and the best fit curve was evaluated to be linear ( $y = ax + b$ ), logarithmic ( $y = a + b \ln x$ ), power ( $y = ax^b$ ), and exponential ( $y = ae^x$ ), where  $x$  is the independent variable and  $y$  is the dependent variable. The statistical credibility of the obtained regression equations was also analyzed using the common statistical indicators such as coefficients of determination ( $R^2$ ), adjusted  $R$ -square (Adj.  $R^2$ ), standard error of estimate (SEE), and analysis of variance (ANOVA). 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. 2018b). The results of the ANOVA test are summarized as  $F$  statistic, the degree of freedom (DF), and the significance of  $F$  (Sig. of  $F$ ). 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).

The results of statistical analyses in the prediction of different physical and mechanical parameters from dynamic hardness scales have been shown in Tables 8 and 9. As can be seen in Table 8, in sedimentary rocks, except for the N-type Schmidt hardness, all other parameters are related to the power distribution with dynamic hardness. Also, among the dynamic hardness methods, the Leeb-UCS and L-type Schmidt-UCS equations are the realistic prediction models in igneous rock samples. Additionally, the values of SEE demonstrate the reliability Leeb hardness regression equation higher than Shore hardness regression models for predicting UCS.

### Effects of physico-mechanical properties on rock hardness

Hardness is one of the dominant mechanical properties of rocks, which affects the machinability and engineering applications of rocks enormously (Hoseinie et al. 2009). Therefore, it is in interaction with many other material properties and is also used to indirectly estimate them. So far, many efforts have been conducted to realize this interaction from a straight rock engineering point of view.

Szlavin (1974) concluded that the Cone indenter hardness test could be considered a suitable instrument for making rapid rock strength assessments and specific energy. Rabia and Brook (1979) have reviewed the effect of length, area,



**Table 7** Empirical formulas for estimating the physico-mechanical properties using various hardness methods

Parameters	Data source	Rock types	Empirical formula	R <sup>2</sup>
E-S.H.H	Bell and Lindsay (1999)	Sandstone samples	-	0.56
γ-S.H	Yaşar and Erdoğan (2004)	Limestone, marble, sandstone, basalt	$\gamma = 1.1623 \ln(S.H) - 2.0925$	0.80
E-S.H.H	Shalabi et al. (2007)	Shale samples	$E = 0.971(S.H) - 26.907$	0.92
E-S.H.H	Dinçer et al. (2008)	Caliche samples	$E = 0.060(S.H) - 0.181$	0.69
BTS-S.H	Altındağ and Güney (2010)	Collected from previous studies	$BTS = 0.0423S.H^{1.2799}$	0.81
γ-L.H	Yüksek (2019)	Tuff, basalt (volcanic rocks)	$\gamma = 6.8379 e^{0.0015(L.H)}$	0.92
n-L.H			$n = -0.0592(L.H) + 57.649$	0.91
w-L.H			$w = -0.051(L.H) + 46.776$	0.90
E-L.H	Aldeeky et al. (2020)	Basalt	$E = 0.0496(L.H) + 18.993$	0.79
UCS-S.H	Teymen (2021)	Plutonic, volcanic, subvolcanic, pyroclastic, sedimentary, metamorphic rocks	$UCS = 0.27(S.H)^{1.45}$	0.66
E-S.H			$E = 0.14(S.H)^{1.2}$	0.57
UCS-B.H			$UCS = 5.1(S.H)^{0.62}$	0.87
E-B.H			$E = 1.54(S.H)^{0.52}$	0.78
UCS-V.H			$UCS = 5.8(V.H)^{0.62}$	0.90
E-V.H			$E = 1.62(V.H)^{0.58}$	0.78
UCS-IHI			$UCS = 6.2(IHI)^{1.08}$	0.71
E-IHI			$E = 2.04(IHI)^{0.87}$	0.64
γ-L.H	İnce and Bozdağ (2021)	Granite, tuff, basalt, andesite, phonolitic basanite, dacite, quartz andesite	$\gamma = 1.124 e^{0.001(L.H)}$	0.85
n-L.H			$n = 45.77 - 0.05(L.H)$	0.87
V <sub>p</sub> -L.H			$V_p = 0.72 + 0.004(L.H)$	0.57

and volume on optimal Shore hardness testing of rocks. Bilgin et al. (1992) concluded a linear correlation between UCS and Cerchar hardness of coal samples. Kolaiti and Papadopoulos (1993) have attempted to modify the limitations of the Schmidt hammer test. They concluded that Schmidt hardness values are influenced by weathering and surface

microstructure anisotropy. Szwedzicki (1998) investigated the empirical indentation index as an indicator of the rock's hardness. The results showed that standardized indentation testing allows for the characterization of rock's mechanical properties and that there is a relationship between the value of the indentation hardness index and the UCS. According

**Table 8** Statistical results of simple regression analyses in sedimentary samples

Variables	The best type of distribution	R <sup>2</sup>	R	Adj. R <sup>2</sup>	F value	Sig. of F	SEE
UCS vs L-type Schmidt	Power	0.70	0.84	0.69	453.13	0.00	0.16
UCS vs N-type Schmidt	Exponential	0.74	0.86	0.73	400.66	0.00	0.55
UCS vs Shore	Power	0.72	0.85	0.71	491.15	0.00	0.55
UCS vs Leeb	Power	0.63	0.80	0.62	355.35	0.00	0.50
E vs Schmidt	Power	0.78	0.88	0.79	354.63	0.00	0.86
V <sub>p</sub> vs Schmidt	Power	0.71	0.85	0.70	106.29	0.00	0.19

**Table 9** Statistical results of simple regression analyses in igneous samples

Variables	The best type of distribution	R <sup>2</sup>	R	Adj. R <sup>2</sup>	F value	Sig. of F	SEE
UCS vs L-type Schmidt	Power	0.80	0.89	0.79	681.83	0.00	0.32
UCS vs N-type Schmidt	Power	0.76	0.87	0.76	359.15	0.00	0.46
UCS vs Shore	Exponential	0.74	0.86	0.73	285.62	0.00	0.56
UCS vs Leeb	Exponential	0.80	0.89	0.79	641.69	0.00	0.43
E vs Schmidt	Power	0.71	0.85	0.70	359.12	0.00	0.62
V <sub>p</sub> vs Schmidt	Power	0.70	0.84	0.69	280.90	0.00	0.15

to Quitete and Rodrigues (1998), for each type of rock, three test specimens with dimensions of  $70 \times 70 \times 30$  mm are applied for the Knoop hardness test by applying a load of 1.96 N at 40 specified locations on the surface of each test specimen. Kahraman et al. (2002) have examined in situ and laboratory Schmidt hammer values for nine types of rocks. They presented a statistical relationship between the laboratory Schmidt hardness and in situ Schmitt hardness. Altindag and Güney (2005) and Aydin (2008) have suggested the methods for determining the Shore and Schmidt hardness, respectively. Viles et al. (2011) have studied the hardness of basalt and dolerite using Schmidt hammer (classic N-type and silver Schmidt BL type) along with two types of Equotip (standard type D and Piccolo) hardness tests. They tried to find the differences between the Equotip and Schmidt hammer values, which may reveal information about the nature of weathering on different surfaces. Boutrid et al. (2013) have investigated the validity of the Brinell hardness test applied to rocks. They conducted that this method is a quick and straightforward method of assessing the properties of rocks. Also, they reported a useful correlation between Brinell hardness and the strength properties of the rock. Ayres da Silva et al. (2015) have established a hardness index called equivalent Vickers microhardness (EVM). They showed that the association of equivalent microhardness with other strength parameters allowed the generation of powerful algorithms to analyze the rock material's behavior under diversified circumstances. Ghorbani et al. (2022a) have developed a new rock hardness classification system based on the Leeb dynamic hardness method. Using this classification system, the rock hardness class can be easily determined using the Leeb portable method. In addition to the above-mentioned fundamental studies, many researchers have studied the relationship between rock hardness and various mechanical and physical properties of rocks in recent years. A vast literature review shows that 14 different parameters affect rock hardness. The details of the past studies are presented in Table 10. As shown in this Table, most of the studies have focused on the effects of sample dimension (size, area, and volume), UCS, and P wave velocity on rock hardness.

### Interconnection of dynamic rock hardness scales

The literature review indicates that very few studies have specifically focused on examining the relationship of rock hardness methods with each other. Nevertheless, based on the regression analysis of the available data sets in the literature, some limited regression analysis has been performed in this paper (Figs 16 and 17). As can be seen in the figures, the achieved models are significantly powerful and

impressive. The results reveal that, due to similar mechanisms and definitions of dynamic hardness testing methods, they have robust correlations and could be simply exchanged with each other.

According to the results of statistical analysis between different dynamic hardness methods, it is observed that the Leeb method with the Schmidt method is closely correlated especially in igneous and sedimentary samples. This means that nowadays, the Leeb method, which is presented digitally with high accuracy and in small instruments, can predict the Schmidt hardness of rocks both in the laboratory and in the site. One of the significant disadvantages of the Schmidt method is the inefficiency in weak rocks, which can be ignored by the Leeb method.

### Role of rock hardness in different fields of rock engineering

Rock hardness tests have been attractive and helpful for geologists, rock, and construction engineers for many years due to the fast and low-cost estimation of rock machinability and excavatability properties. Therefore, a vast range of laboratory and field studies has been carried out to accurately determine the relationships and any possible models to predict the rock material properties. This paper has surveyed the available literature in this regard from the viewpoint of hardness and its effects on rock machinability. The main general areas which have been focused on the literature survey are as follows:

- Rock mass drillability and drilling rate prediction
- Excavatability (diggability, rippability, and blastability)
- Abrasion and wear rate prediction
- Crushing, specific energy, and Bond work index
- Sawability and production rate of ornamental stones
- Rock mass cuttability
- Tool life estimation

Table 11 reviews most of the studies on the relationship between excavation operation properties and hardness testing methods. As can be seen in this table, most available methods in rock hardness measurement have been used to evaluate excavation operational parameters. Also, according to the number of studies performed based on each hardness method, the importance of each hardness method in the field of rock engineering can be understood. Among the methods analyzed in Table 11, as can be seen, the Schmidt and Shore hardness methods have a wider application in the field of rock excavation.

With an in-depth analysis of all available literature and reported researches, it was found that hardness is a critical factor in rock mass excavatability assessment and has

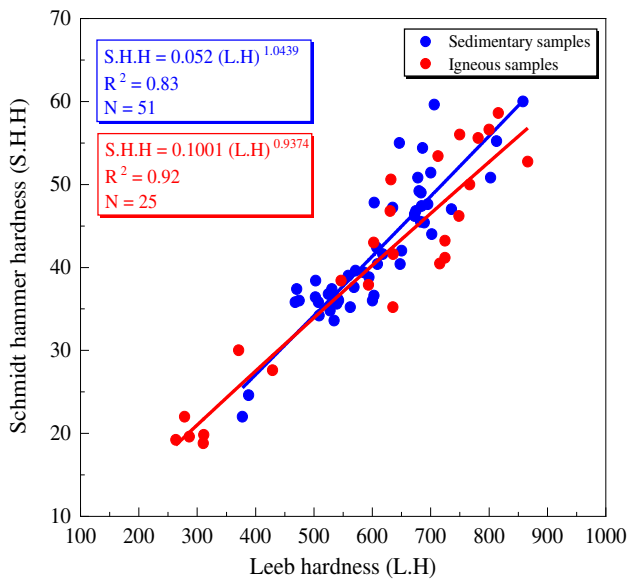
**Table 10** Results of the literature review on physicommechanical parameters affecting the rock hardness

Reference	Rock parameters*													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Szlavin (1974)			•											
Irfan and Dearman (1978)			•	•				•						
Rabia and Brook (1979)	•													
Atkinson et al. (1986)			•											
Sachpazis (1990)			•	•										
Ojo and Brook (1990)									•					
McCarroll (1991)													•	
Coquard and Boistelle (1994)									•					
Ersoy and Waller (1995)												•		
Christaras (1996)							•							
Arthur (1996)			•	•				•		•				
Bobji et al. (1999)													•	
Matsukura and Tanaka (2000)														•
Altindag (2002)	•	•												
Sumner and Nel (2002)									•					
Mutlutürk et al. (2004)		•												
Ozturk et al. (2004)												•		
Altindag and Güney (2005)	•													
Su and Akçın (2005)			•											
Yavuz et al. (2006)		•												
Altindag and Güney (2006)										•				
Chary et al. (2006)							•							
Aydin (2008)										•				
Sabatakakis et al. (2008)					•	•								
Basu et al. (2009)														•
Demirdag et al. (2009)	•													
Del Potro and Hürlimann (2009)					•									
Niedzielski et al. (2009)	•													
Gupta et al. (2009)													•	
Khandelwal and Ranjith (2010)							•							
Kurtuluş et al. (2010)							•							
Sengun et al. (2011)							•							
Diamantis et al. (2011)							•							
Yagiz, 2011a, b							•							
Ozbek and Gul (2011)			•		•	•								
Yavuz (2011)		•												
Ribeiro et al. (2011)													•	
Arikan and Aydin (2012)														•
Ündül and Tuğrul (2012)														•
Khandelwal (2013)							•							
Ozguven and Ozcelik (2014)		•												
Sousa (2014)							•							
Sengun (2014)		•												
Khanlari et al. (2014)														
Abdmusalib et al. (2015)						•								
Kallu and Roghanchi (2015)	•													
Fereidooni (2016)						•								
Asiri et al. (2016)	•													
Kurtuluş et al. (2016)							•							
Sajid et al. (2016)			•											
Freire-Lista et al. (2016)		•												
Tiskatine et al. (2016)		•			•	•						•		

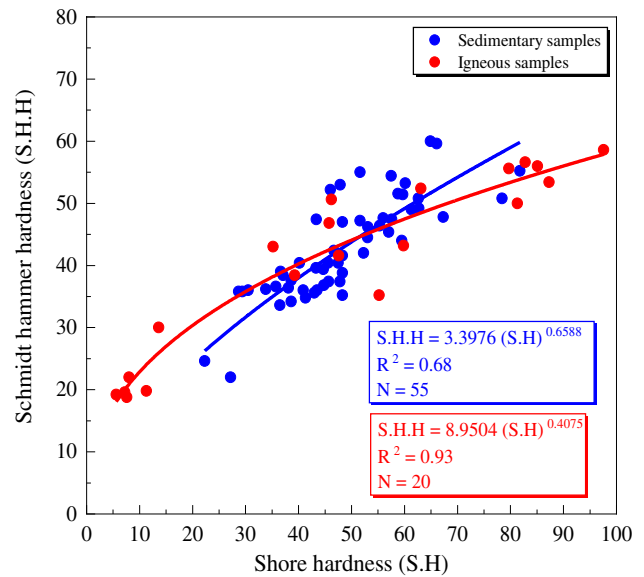
**Table 10** (continued)

Reference	Rock parameters*													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Aghamelu and Amah (2017)										•				
Yaralı (2017)			•					•		•				
Zhang et al. (2017a, b)		•												
Boulenouar et al. (2017)				•										
Corkum et al. (2018)	•		•											
Khandelwal (2018)							•							
Yilmaz and Goktan (2018)														
Demirdag et al. (2018)										•				
Özbek et al. (2018)											•			
Tumac et al. (2018)													•	
Comakli and Cayirli (2019)													•	
Atici and Comakli (2019)													•	
Yilmaz and Goktan (2019)						•								
Desarnaud et al. (2019)	•					•			•					•
Chen et al. (2019)														•
Leão et al. (2019)														•
Park et al. (2020)		•												
Sun et al. (2020)				•										
Zhang et al. (2020)		•												
Ghorbani et al. (2022b)							•							

\*A, sample dimension (thickness, area, and volume); B, temperature (as well as freeze-thaw cycles); C, uniaxial compressive strength; D, Young’s modulus; E, unit volume weight or density; F, porosity; G, ultrasonic P wave velocity; H, point load strength; I, moisture content; J, tensile strength; K, anisotropy; L, micro-fabric characteristics; M, surface roughness; N, weathering



**Fig. 16** Correlations between Schmidt hardness and Leeb hardness (data collected from (Çelik and Çobanoğlu 2019; Yilmaz and Goktan 2019))



**Fig. 17** Correlations between Shore hardness and Schmidt hardness (data collected from (Bell and Lindsay 1999; Tiryaki et al. 2001; Yaşar and Erdoğan 2004; Güney et al. 2005; Çelik and Çobanoğlu 2019))



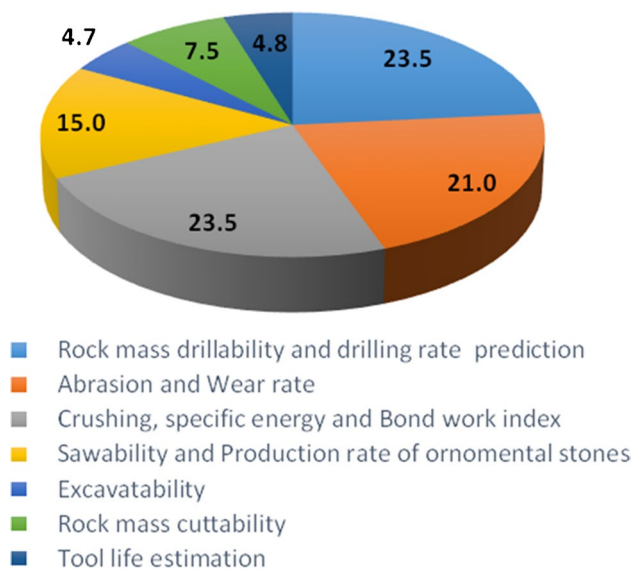
**Table 11** Results of literature review of rock hardness effect on excavation operational properties

Rock hardness method	Excavation operational properties							Reference
	A	B	C	D	E	F	G	
Shore	•		•	•	•	•		Szlavin (1974); McFeat-Smith and Fowell (1977); Muro (1988); Eyuboglu et al. (2003); Keleş (2005); Yavuz et al. (2005); Ersoy et al. (2005); Tiryaki (2006), (2008), (2009); Tumac et al. (2007), (2013); Ugur et al. (2010); Güney (2011); Yarali and Soyer (2011), (2013); Yılmaz et al. (2011); Aydin et al. (2013b), (2013a); Bayram (2013); Sengun and Altindag (2013); Ekincioglu et al. (2013); Engin et al. (2013); Tumac (2014); He et al. (2016); Kahraman (2016); Sun et al. (2016); Dogruoz et al. (2016); Er and Tuğrul (2016a), (2016b); Çobanoğlu and Çelik (2017b); Mikaeil et al. (2018b); Ozdogan et al. (2018); Tumac and Shaterpour-Mamaghani (2018); Guney (2019), Buyuksagis et al. (2020)
Mohs	•	•	•	•	•			Jimeno et al. (1995); Sapigni et al. (2002); Ersoy et al. (2005); Hoseinie et al. (2020), (2008), (2009), (2012), (2014); Yılmaz (2011); Ataei et al. (2012a); Mikaeil et al. (2013), (2018a); Saeidi et al. (2013); Aydin et al. (2013a); Almasi et al. (2017b), (2017a); Faria et al. (2017); Jamshidi (2019)
Schmidt	•	•	•	•	•	•	•	Rabia and Brook (1980); McLean and Gribble (1985); Howarth et al. (1986); Karpuz (1990); Kahraman (1999); Bilgin and Kahraman (2003); Kahraman et al. (2003); Basarir and Karpuz (2004); Balci et al. (2004); Ersoy et al. (2005); Goktan and Gunes (2005); Keleş (2005); Goktan and Gunes (2005); Bilgin et al. (2006); Tiryaki and Dikmen (2006); Fener et al. (2007); Kahraman and Gunaydin (2007); Tutmez et al. (2007); Basarir et al. (2008); Yavuz and Ugur (1997); Adebayo et al. (2010); Ugur et al. (2010); Güney (2011); Mikaeil et al. (2011); Sharma et al. (2011); Yagiz (2011a); Cheniany et al. (2012); Hoseinie et al. (2012, 2014, 2020); Ataei et al. (2012b, 2015); Sengun and Altindag (2013); Tumac et al. (2013); Yarali and Soyer (2013); Aydin et al. (2013a, 2013b); Demirdag et al. (2014); Arslan et al. (2015); Korman et al. (2015); Shafique and Bakar (2015); Tumac (2015); Yılmaz et al. (2015); Bilgin et al. (2015); Chandar et al. (2016); Dogruoz et al. (2016, 2018); Er and Tuğrul (2016a), (2016b); Yetkin et al. (2016); Capik and Yılmaz (2017a), (2017b); Capik et al. (2017); Çobanoğlu and Çelik (2017b); Liang et al. (2017); Mohamad et al. (2017), (2019); Adeyemo et al. (2018); Fereidooni and Khajevand (2018); Tumac and Shaterpour-Mamaghani (2018); Yenice et al. (2018); Bakar et al. (2018); Ali et al. (2019); Guney (2019); Majeed et al. (2020), Buyuksagis et al. (2020)
Knoop			•	•				Aydin et al. (2013b); Goktan and Yılmaz (2017); Sarıışık and Özkan (2018), Buyuksagis et al. (2020)
Vickers			•	•	•		•	Johannessen et al. (1995), Sánchez Delgado et al. (2005), Yılmaz (2011), Gent et al. (2012), Aydin et al. (2013a), Hassanpour et al. (2014), Ayres da Silva et al. (2015), Macias et al. (2016), Hassanpour (2018); Majeed et al. (2020)
Rosiwal			•	•				Yılmaz (2011), Buyuksagis et al. (2020)
Cerchar hardness index			•	•		•		Rajpurohit et al. (2018), (2020), Buyuksagis et al. (2020)
Rockwell				•				Haffez (2012)
Cone indenter hardness			•	•				McFeat-Smith and Fowell (1977); Fowell and Pycroft (1980); Tiryaki (2006), (2008), (2009); Tiryaki and Bolukbasi (2007); Bayram (2013); Dogruoz et al. (2016); Doğruöz and Bolukbasi (2017)
Indentation hardness test	•				•			Kahraman and Gunaydin (2008); Hoseinie et al. (2012)

A: Rock mass drillability index and Rock penetrability index; B: Excavatability (Digging, Ripping, and Blasting methods); C: Abrasion and Wear rate; D: Specific energy and Bond work index; E: Sawability and Production rate; F: Rock mass cuttability index and cutting rate; G: Tool life estimation

been applied in various forms and using different standards. Figure 18 shows the results of a survey in the past 50 years of rock and excavation literature. Statistical analysis was performed to ascertain the area with the highest number of hardness applications. As shown in Fig. 18, rock hardness

has been applied in drillability studies, wear analysis, specific energy, and sawability more than in other research areas. In other words, around 80% of the past literature is focused on the relationship between the mentioned concepts and rock hardness. Additionally, the remarkable point is that



**Fig. 18** Frequency of the applications of rock hardness in past literature

two dynamic hardness testing methods, including Shore and Schmidt, have been applied more than all others.

## Conclusion

The current paper is intended to discuss rock hardness testing methods and their applications in rock engineering. The investigation shows that dynamic methods have been widely used more than static methods by rock mechanics researchers and geological engineers. Static methods suffered from disadvantages compared to dynamic methods from several perspectives. Measurement accuracy (recognition of diagonal indentation length in methods with indentation mechanism), time of analysis (mineralogical and petrographic analysis in Mohs method with scratching mechanism, and Rosiwal method with grinding mechanism), and cost of experiments could be mentioned as the main disadvantages of static methods. On the other hand, it is evident from the literature that accurate measurement and full understanding of the rock hardness value and class depend on experimental techniques and testing procedures in the laboratory.

A vast literature review shows that 14 different parameters affect the rock hardness initially. Most studies focus on the relationship of rock hardness with sample dimension (size, area, and volume), UCS, and P wave velocity. Based on regression analysis in this paper, among three dynamic hardness scales, it seems that the Leeb hardness establishes the best correlation with the UCS. In this review, the application of rock hardness methods in seven groups of the most

widely used parameters in the field of drilling engineering has been classified and analyzed. Based on the literature survey, most of the conducted studies are related to the four parameters, including drillability, wear, specific energy, and sawability. In other words, about 80% of the sources have focused on the relationship of rock hardness methods with the above four parameters.

Therefore, in general, it can be said that the rock hardness parameter, especially rock hardness methods with dynamic mechanisms, can be used to predict other physical and mechanical properties of rocks. Of course, it is necessary to mention that the accuracy of prediction by various hardness methods is different, but in any case, it can be useful for the initial prediction and pre-feasibility studies of rock engineering projects.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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