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Methods and Instruments for Measuring Rock Hardness

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ABSTRACT

Hardness is a crucial property and indicator of materials, representing their ability to resist the penetration of hard objects into their surface. Particularly in rock mechanics, rock hardness not only serves as a measure of the difficulty in fracturing rocks but is also closely related to rock drillability (i.e., the resistance of rocks to drilling), compressive strength, drill bit selection, drilling efficiency, and rock fragmentation methods. Therefore, in the field of mechanical drilling, the accurate determination of rock hardness becomes critically important. With the advancement of science and technology, humanity has progressively deepened its understanding and research on rock hardness, leading to the invention of various instruments for measuring it. Industrial development has gradually phased out primitive measurement methods such as scratching and scoring, making rock hardness measurements increasingly accurate and steering the process onto a scientific track. This investigation, from the perspective of rock hardness, delves deeply into this significant mechanical property, examines the domestic and international background of rock hardness measurement techniques, summarizes the instruments, tools, methods, principles, and characteristics of rock hardness measurement, and offers insights into the future development prospects of rock hardness measurement.

KEYWORDS

Rock; Rock Mechanics; Hardness; Measurement.

1. INTRODUCTION

Hardness refers to the ability of a material to resist the penetration of a hard object into its surface, serving as an indicator for measuring the softness or hardness of a material. Depending on the measurement method, hardness can be classified into scratch hardness, indentation hardness, and rebound hardness. Indentation hardness can be further subdivided into Brinell hardness, Rockwell hardness, Vickers hardness, etc. [1]. Rock, as a general term for a category of materials, has a hardness that reflects its ability to resist the intrusion of harder external objects into its surface. In practical engineering applications, the hardness of rock indicates the softness or hardness level of the entire formation's rock, as well as the difficulty or ease of drilling. It serves as critical foundational data for the selection and design of drill bits [2].

Due to the intricate and varied nature of natural environments, rock hardness is subject to multiple influencing factors that require careful consideration during measurement.

The type of rock is a key factor influencing its hardness. In nature, rocks exhibit significant diversity. Based on their hardness characteristics, they can be broadly classified into hard rocks and soft rocks. According to specific physical properties (such as unit weight, relative density, etc.), they can be further categorized and named into common types like granite, limestone, sandstone, shale, and slate. Based on gravel and cobble content, they can be subdivided into boulders, crushed stone, and pebbles

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[3]. “Rock” is a general term, and based on formation mechanisms, there are three major categories: igneous rocks, sedimentary rocks, and metamorphic rocks [4]. Different rock types exhibit variations in internal structure, physical properties, and content of hard minerals. Generally, the greater the content of hard minerals, the higher the hardness of the cementing material, and the finer the rock grains, the denser the rock structure and the greater the rock hardness.

Bedding is also a significant factor influencing rock hardness. Rock hardness exhibits notable anisotropy, being minimal in the direction perpendicular to bedding and maximal in the direction parallel to bedding.

Pressure and drilling parameters are also significant factors influencing rock hardness [5]. Under uniform confining pressure, rock hardness increases. At atmospheric pressure, rock hardness remains relatively low. The growth rate of rock hardness accelerates with increasing confining pressure. During rock fragmentation, the drill bit not only rotates at high speed but also sustains continuous downward impact. As drilling depth increases, rock hardness undergoes corresponding changes, necessitating adjustments in drilling speed accordingly.

It is precisely the in-depth investigation of these multifaceted factors that has standardized and refined the measurement of rock hardness, while simultaneously elevating the development of corresponding instrumentation to new heights.

2. DOMESTIC AND INTERNATIONAL DEVELOPMENT OF ROCK HARDNESS MEASUREMENT

2.1. International Development of Rock Hardness Measurement

The measurement of material hardness originated earlier and developed rapidly in foreign countries. As early as 1722, French physicist Réaumur pioneered a highly rudimentary scratch hardness testing method [6]. He used the hardness of seven other substances as standards to determine the relative hardness of metals. Subsequently, various methods for measuring the hardness of object materials were invented. In 1822, German scientist Friedrich Mohs proposed a new hardness measurement method—the Mohs hardness scale—as a standard for measuring mineral hardness, which later gained widespread application. In 1876, Englishman Albert Shore introduced Shore hardness, whose measurement principle also differed from that of the Mohs method and significantly enhanced the accuracy of hardness determination. Fig. 1 shows a Shore hardness tester manufactured by IMAI SIKENKI Equipment Co.

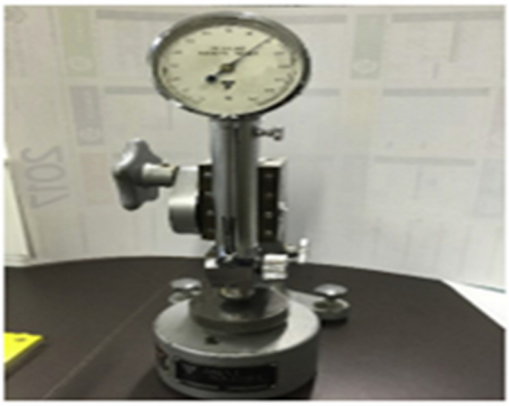

Fig 1. Shore hardness tester

In 1900, Swiss engineer J.A. Brinell proposed the concept of Brinell hardness as a standard for measuring material hardness. The Brinell hardness method, known for its measurement accuracy and strong repeatability, has been widely adopted for material hardness testing. Within the following

century of development, American inventor Hugh M. Rockwell introduced Rockwell hardness in 1914. British engineers Smith and Sandland proposed Vickers hardness in 1921, American scientist Frederick Knoop developed Knoop hardness (also known as microhardness) in 1939, and Swiss engineer Leeb introduced Leeb hardness in 1978. With ongoing industrialization and informatization, these historically established methods and their underlying principles remain enduringly relevant, having evolved into mature, classical techniques that continue to be extensively applied today.

2.2. Domestic Development of Rock Hardness Measurement

For a considerable period in the past, the concept of hardness testing was absent in China. Material hardness could only be estimated empirically by seasoned masters through observing sparks or listening to the sound of metal impacts on site. By the early years of the nation's founding, a few state-owned enterprises began developing the first hardness testers domestically. With the advent of reform and opening-up, a large number of private enterprises emerged in the field of hardness tester manufacturing, leading to rapid development in both the production volume and variety of domestic hardness testers [7]. Fig. 2 shows a portable Mohs hardness tester developed in China. By analyzing the scratch left on a mineral surface after friction with the tester's needle tip, operators can estimate the hardness of the mineral or rock. This tester is equipped with eight needle tips of different hardness values, enabling it to meet the needs of various hardness testing requirements [8].

Fig 2. Portable mohs hardness tester

Furthermore, Brinell hardness testers exemplify the vigorous development of China's hardness testing instrumentation. In recent years, with the rapid advancement of on-site Brinell hardness testing technology, innovative methods have continuously emerged. China has made significant progress in Brinell hardness testers and, to meet production demands, has developed various models capable of adapting to diverse operational conditions [9]. Fig. 3 shows an impact-type Brinell hardness tester. The device contains a spring, a compression spring, and a release mechanism internally, with a small steel ball positioned at its tip.

Fig 3. Impact brinell hardness tester

Fig. 4 shows a hammer-type Brinell hardness tester, which consists of a support frame, a steel ball, and an oblong hardness test block.

Fig 4. Hammer blow brinell hardness tester

3. TECHNIQUES AND INSTRUMENTATION FOR ROCK HARDNESS MEASUREMENT

3.1. Mohs Hardness Method

3.1.1. Principle

The Mohs hardness scale, also referred to as Mohs hardness, is a classic scratch hardness method. Due to its simplicity and practicality, it is widely used by field geologists for mineral identification. To determine mineral hardness, ten naturally occurring minerals with significantly different hardness levels are selected as benchmarks for the ten grades of the scale. Relative hardness is determined through mutual scratching tests [10, 11, 12]. Among these, talc is the softest (Grade 1), while diamond is the hardest (Grade 10). The remaining minerals are assigned as follows: gypsum (Grade 2), calcite (Grade 3), fluorite (Grade 4), apatite (Grade 5), feldspar (Grade 6), quartz (Grade 7), topaz (Grade 8), and corundum (Grade 9) [13, 14]. The distribution of these grades is shown in Table 1.

Table 1. Classification of mineral hardness grade

Mineral	Grade
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Feldspar	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

3.1.2. Characteristic

The Mohs hardness method is simple and practical, but most rocks are not composed of a single component, but are composed of a combination of multiple components. Therefore, relying solely on this method to determine rock hardness, measurement personnel cannot obtain accurate data.

3.2. Shore Hardness Method

3.2.1. Principle

The Shore hardness method belongs to the elastic rebound method. The measuring personnel first prepare a diamond or alloy punch of a specified quality and shape, allowing it to fall freely from a certain height. The punch impacts the surface of the specimen and then bounces back. By testing the rebound height, the tester can determine the hardness of the specimen [15]. The Shore hardness has no unit, and its hardness is represented in the following order: hardness value, Shore hardness symbol HS, hardness tester type symbol C or D [16].

3.2.2. Device

The Shore hardness tester can be used to measure the Shore hardness of the sample. Fig. 5 is a schematic diagram of a Shore hardness tester.

Fig 5. Shore hardness tester

3.2.3. Expression

The Shore hardness has no unit, and its hardness value is the ratio of the height at which the punch impacts the material and the initial height at which the punch falls. Generally, multiple measurements are taken to take the average value. It can ultimately be determined according to equation (1):

$$\mathrm{Hs} = \sum_{n}^{20} H\mathrm{si}\,/n \tag{1}$$

3.2.4. Characteristic

Shore hardness is a convenient and inexpensive method for estimating rock hardness, which can be used as a reliable predictive indicator for other mechanical properties [17, 18]. However, it is a test for a certain point of the material, and due to the uneven material of the sample, the height of each rebound of the punch may differ too much, which can easily cause errors for the measuring personnel during the measurement process.

3.3. Rockwell Hardness Method

3.3.1. Principle

Rockwell hardness is an indicator that determines the hardness value by the depth of indentation plastic deformation. When measuring, the measuring personnel use a diamond cone with a top angle of 120 degrees or a steel ball of a specified diameter to press into the surface of the tested material under a certain load, and the hardness of the material is determined by the depth of the indentation. The specific experimental principle is as follows: the tester uses a special indenter to first apply a preload to obtain a pressing depth h_0, and then applies a main load. The indenter continues to press into the interior of the specimen, and then removes the main load while retaining the preload to obtain the depth h_1 of the material after elastic recovery. The hardness value is determined by the residual pressing depth $e=h_1-h_0$, which can generally be directly read from the instrument [19, 20,21].

3.3.2. Device

The instrument used to measure Rockwell hardness is the Rockwell hardness tester. There are two basic types of Rockwell hardness testers, one is a 120 degree conical diamond indenter (divided into C and A types), and the other is a hard alloy ball indenter (B type indenter). The former is used for testing hard materials, while the latter is used for testing the hardness of soft materials [22]. Fig. 6 is a schematic diagram of the Rockwell hardness tester.

Fig 6. Rockwell hardness tester

3.3.3. Characteristic

This method is easy to operate, with small indentation and a wide range of hardness values for measurement. However, it is sensitive to the unevenness of the internal structure of the material, and is prone to significant errors or even instrument damage during measurement due to certain human factors or the influence of the tested sample [23].

3.4. Vickers Hardness Method

3.4.1. Principle

Vickers hardness is a type of indentation hardness. It uses a regular square pyramid diamond indenter with a relative angle of 136 degrees to press it into the material surface under a certain load. After holding for a specified time, the test force is removed, the diagonal length d of the indentation on the sample surface is measured, and the indentation surface area is calculated. Finally, the average pressure on the indentation surface area is calculated to obtain the Vickers hardness value of the test material [24, 25, 26].

3.4.2. Device

The instrument used to measure Vickers hardness is the Vickers hardness tester. Vickers Armstrong, a British company, manufactured the world's first Vickers hardness tester. Vickers hardness tester is a high-tech product that integrates optics, mechanics, and electronics. Researchers can classify Vickers hardness into various types from the perspective of force and the way force is applied. Fig. 7 shows a fully functional Vickers hardness tester.

Fig 7. Full function vickers hardness tester

3.4.3. Characteristic

Vickers hardness has the highest accuracy, good repeatability, and a wide range of hardness values among commonly used hardness measurement methods. Its testing indentation is small, making it suitable for testing the hardness of thin and small materials. But the technical requirements for the experiment are high, and the efficiency is therefore low. However, with the continuous development and optimization of modern technology, this disadvantage has gradually been overcome.

3.4.4. Expression

The Vickers hardness value can be obtained by looking up a table or determined according to the following equation (2):

$$HV = 0.102 \times F/S \approx 0.189 \times F/d^2 \quad (2)$$

Among them: *Hv* is Vickers hardness; *S* is the indentation area; *F* is the experimental force; *d* is the average of the diagonals of two indentations.

3.5. Brinell Hardness Method

3.5.1. Principle

Measurement personnel use a certain size of test load to press a quenched steel ball or hard alloy ball of a certain diameter into the surface of the tested material, maintain it for a certain period of time, and then remove the load to obtain an indentation. The diameter of the indentation on the surface of the sample is measured, and the value obtained by dividing the test force by the indentation surface area is the Brinell hardness value [27, 28, 29].

3.5.2. Device

The instrument used to measure Brinell hardness is the Brinell hardness tester. With the rapid development of on-site Brinell hardness testing technology, new technologies emerge one after another, and many past defects have been compensated for. The manufacturing technology of Brinell hardness testers has also made significant progress [30]. The shear pin hammer Brinell hardness tester shown in Fig. 8 consists of a shear pin frame, shear pin, spherical indenter, sleeve, and support handle.

Fig 8. Shear pin hammer Brinell hardness tester

Fig 9. Swing arm brinell hardness machine

Fig. 9 shows a rocker arm Brinell hardness machine, consisting of a base, a column, a rocker arm, a vertical moving unit, a measuring head, an electrical control box, an indentation reading device, and a measuring table.

Fig. 10 shows a door type Brinell hardness machine, which consists of a base, steel rails, loading vehicle, gantry, vertical moving unit, measuring head, electrical control cabinet, and indentation measuring device.

Fig 10. Door type brinell hardness machine

3.5.3. Expression

Generally, the Brinell hardness value can be calculated by directly reading the table, or by dividing the test force by the indentation spherical surface area after knowing the relevant parameters [31]. Determine according to equation (3):

$$H_B = F/S = F/\pi(d/2)^2 \quad (3)$$

Among them, F is the force pressed into the surface of the material; S is the indentation area; d is the average diameter of the indentation.

3.6. Abrasion Hardness Method

3.6.1. Principle

The wear hardness method refers to the measurement of hardness based on the change in sample mass before and after wear, when the sample surface is subjected to wear under a specified uniform external force [31, 32].

3.6.2. Device

The wear hardness of the sample can be measured using a wear tester. Fig. 11 shows a certain wear testing machine, consisting of a column, grinding disc, sand hopper, sample clamp, and pulley.

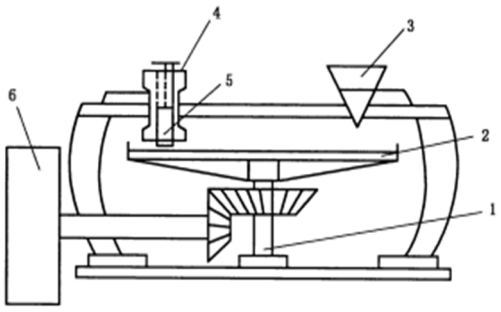

Fig 11. Wear testing machine

In the Fig. 11, 1 is the column; 2 is the grinding disc; 3 is a sand bucket; 4 is the sample holder; 5 is the sample; 6 is the pulley.

3.7. Leeb Hardness Method

3.7.1. Principle

Leeb hardness refers to the measurement of the impact velocity and rebound velocity at a distance of 1mm from the surface of a test specimen when a certain mass of a punch body is impacted under a certain test force. The Leeb hardness value is expressed as the ratio of the rebound velocity of the punch body to the impact velocity [33].

3.7.2. Device

The Leeb hardness of rocks can be measured using a Leeb hardness tester. Fig. 12 is a schematic diagram of a Leeb hardness tester.

Fig 12. Leeb hardness tester

3.7.3. Characteristic

The Leeb hardness can be determined according to formula (4):

$$H_L = 1000 \times V_b / V_a \tag{4}$$

Among them, H_L is the Leeb hardness; Va is the impact velocity of the punch; Vb is the rebound speed of the punch.

3.7.4. Expression

Leeb hardness is widely used and has a large measurement range. Mold cavities, heavy workpieces, bearing parts, and so on can all be measured and expressed using Leeb hardness. There are many types of Leeb hardness, which will continue to develop towards higher accuracy, better reliability, smaller size, lighter weight, and stronger functionality [34].

3.8. Rock Hardness Recognition based on BP Neural Network Theory

3.8.1. Principle

When the drilling rig is working, record the relevant parameters of the drilling rig, such as feed pressure, rotary pressure, drilling speed, and rotary speed. Select the relevant parameters and establish a functional relationship Y = f (X_1, X_2, X_3, X_4) with rock hardness. X is the input of the relevant parameters, and Y is the output of rock hardness [35, 36].

3.8.2. Device

Generally, they are related drilling drill bits, such as the 1190E roller drill bit shown in Fig. 13.

Fig 13. Drill bit of 1190E rotary drilling rig

3.9. Rock Rebound Test

3.9.1. Principle

Rock rebound test, also known as rebound method, is a convenient and non-destructive testing method. Originally used to evaluate the strength of concrete, it gradually became popular in the field of rocks in the 1960s. Rock rebound testing and related research have made good progress both domestically and internationally. Due to the numerous factors affecting rocks, further improvement is needed for issues related to rock rebound [37, 38]. It uses the elastic loading rod of a rebound hammer (i.e. Schmidt hammer) to impact the surface of the rock. Part of the impact energy is converted into the work that causes deformation of the rock, while the other part of the energy is the rebound distance of the loading rod impact, which is the rebound value obtained [39, 40].

3.9.2. Device

Rebound tester, also known as Schmidt hammer, is convenient and portable, capable of quickly measuring the surface hardness of rock masses or rock blocks on site and obtaining rebound values [41, 42].

3.10. Estimation of Relative Hardness of Rocks Using Laser-Induced Breakdown Spectroscopy

Laser induced breakdown spectroscopy technology, also known as LIBS, focuses ultra short pulse laser on the surface of the sample to form a plasma, and then further analyzes the plasma emission spectrum to determine the material composition and content of the sample. Laser induced breakdown spectroscopy technology can analyze samples in any state (solid, liquid, gas), only affected by laser power, detector sensitivity, and wavelength range. In addition, almost all elements emit characteristic spectral lines when excited to form plasma, making LIBS technology capable of analyzing most elements. LIBS technology is similar to other laser analysis techniques, such as vibrational spectroscopy in Raman spectroscopy and fluorescence spectroscopy in laser-induced fluorescence, which can provide a deeper understanding of the physical properties of samples.

Laser induced spectroscopy technology is an emerging technique used for simultaneous multi-element analysis of solids, liquids, and gases with minimal or no sample preparation. Compared with many traditional techniques, it has multiple advantages and has therefore received great attention and application.

In 2006, LIBS was first used to test the hardness of concrete samples with different humidity levels. Its main idea is based on the correlation between the ratio of ion to atomic line emission and Vickers

surface hardness [43]. Subsequently, Labutin and Cowpe used LIBS technology to investigate the effect of mechanical hardness of aluminum lithium alloys and bioceramics with different element compositions on plasma excitation temperature. Messaoud and Bendib also used LIBS technology to study the relationship between surface hardness of Fe-V-C alloys and plasma temperature, and obtained a linear relationship between Vickers surface hardness and laser-induced plasma temperature [44, 45, 46].

In 2007, Salam et al. estimated the hardness of calcified tissue by measuring the intensity of calcium and magnesium ions and atomic lines using laser-induced spectroscopy, and confirmed that the hardness of the material is proportional to the shock wave velocity and the ratio of ions to atomic lines [47].

Around 2021, Panya et al. also used LIBS technology to study the relationship between rock hardness and plasma excitation temperature, observed the existence of a relationship between sample hardness and density, and found a linear relationship between Te and rock hardness in the sample. Therefore, the surface hardness of geological samples can be estimated by measuring Te [48].

Nowadays, LIBS technology is mainly a qualitative and semi quantitative spectroscopic technique that has been successfully used to determine the hardness of various materials. Compared with traditional methods, it has simple, fast, and real-time measurement capabilities. It allows for in-situ analysis with little or no sample preparation, which is very practical for analyzing geological samples, especially for rock masses that cannot be reached by traditional tools other than hardness measurement.

4. DEVELOPMENT PROSPECTS OF ROCK HARDNESS MEASUREMENT

For hundreds of years, people have invented many traditional hardness measurement methods, such as static pressure test, scratch test, rebound test, cutting method, etc. Among them, static pressure test method is the most mature, and common Brinell, Rockwell, and Vickers belong to this category [49]. In recent years, with the rapid development of microelectronics and computing technology, the demand for industrial product quality and variety, as well as the urgent need for new testing methods, has led to significant progress in hardness testers [50]. In the future, hardness testers will develop towards three major directions: improving test accuracy, further achieving automation of the test process, and using new experimental methods [51].

With the further development and application of optical projection technology, electronic measurement technology, and computer digital processing in measurement, the measurement accuracy of hardness testers will continue to improve. The semi automation and full automation of hardness measurement are not only to meet the needs of development, but also to reduce human errors, improve measurement accuracy and indentation accuracy. The extensive use of photoelectric sensing technology, computer control, and data processing has also promoted the automation of hardness measurement. On this basis, the measurement methods of hardness testers will be further enriched, such as electromagnetic hardness measurement method, ultrasonic hardness measurement method, etc. I believe that with the further development of science and technology in China, the development of rock hardness measurement and hardness testers will reach a new level.

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