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Experimental Study of Effects of Mechanical Properties of Rocks on Wear of Cutting Tools using a New Small-Scale Linear Cutting Machine

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Abstract

Today, due to technological advancements and increasing demand, various types of Tunnel Boring Machines (TBM) are extensively used for tunneling in both soil and rock. The mechanical excavation method has become attractive in tunnel excavation and underground spaces due to its high safety, rapid progress rate, low human labor requirement, and mechanization capability. The high capital costs of mechanical excavation make it essential to conduct laboratory tests, such as linear cutting tests on rocks, before selecting the machine type and adjusting the cutter head blade. The main objective of this study is to investigate the impact of rock mechanical properties on the cutting tool wear using a newly developed small-scale Linear Cutting Machine (LCM). To achieve this, laboratory linear cutting tests on rocks were conducted after constructing the small-scale linear cutting machine. To evaluate the rock cuttability and analyze the performance of disc cutters, 5 rock samples were used at three different penetration depths of 1, 1.5, and 2 mm. The results showed that the wear values of the cutting discs increased with penetration depth in all rock types, with the highest wear observed in basalt. Additionally, Brazilian tensile strength exhibited the highest correlation with cutting disc wear parameters. Furthermore, these studies indicated that determining the mineralogical and physical characteristics of rocks, such as texture, crystal size, and porosity, alongside their mechanical properties, is crucial for predicting rock wear.

1. Introduction

Rocks are characterized by their strength, breakability, and abrasiveness. Cutting tool wear affects productivity for two main reasons: the interaction between the rock and the cutting tool, and the tool's useful life. Wear increases costs and causes delays due to the time required for replacing cutting tools. Various types of wear occur during the disc-based rock-cutting process. This wear causes deformation of the discs, especially their cutting ring, and the type of wear is determined based on the kind of deformation. In recent years, the use of mechanical excavation machines, such as full-face tunnel boring machines (TBMs), has significantly increased in civil and mining projects. Laboratory rock-cutting tests have played a crucial role in selecting, designing, and predicting the performance of these machines. Cutting ability is an essential characteristic of rocks in mechanical excavation, representing their resistance to penetration by excavation tools such as chisels and roller bits. This property can be determined using full-scale rock-cutting tests (FSRCT) and small-scale rock-cutting tests (SSRCT) in the laboratory. Experience gained from laboratory rock-cutting tests demonstrates the method's success, reliability, and efficiency in analyzing the interaction between the tool and the rock. These tests are also considered tools for estimating the forces and specific energy of rock cutting. The cutting forces obtained from FSRCT and SSRCT are used in the design of excavation machines, blade selection, determining optimal blade geometry, predicting costs, and machine performance. In recent years, due to the ease of obtaining smaller samples and

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the simplicity and lower cost of conducting tests, small-scale tests have been used more than large-scale rock-cutting tests. Roxborough and Phillips (1975) presented the first theoretical model for estimating cutting forces on V-shaped disc blades [1]. Zhang et al. (2003) conducted laboratory calibration to measure cutting forces equipment and then measured the main characteristics of cutting forces and crack lengths in rock samples. Additionally, they investigated the relationship between crack lengths and cutting forces [2]. Entacher et al. (2013) developed a novel method to determine the loading components on disc blades in Australian projects and applied it to three TBM disc blades [3]. This designed Sarfarazi et al. (2017) investigated the impact of TBM disc spacing structure was only suitable for actual TBM disc blades. They also examined the relationships between cutting forces and geological features in tunnel face operations [4]. Tumac and Balci (2015) presented a new model for predicting normal and tangential forces applied to CCS-type cutting discs based on developing an efficiency, specifically in rocks with different tensile strengths using PFC2D simulations. Their findings revealed that the optimal disc spacing-to-penetration depth ratio varied significantly based on rock tensile strength, which influenced TBM cutting efficiency. Statistical analysis showed a clear relationship between increased tensile strength and the need for closer disc spacing to maintain effective penetration rates. These results underscored the importance of customizing TBM disc configurations based on specific geological conditions to optimize tunneling performance. Empirical model of V-shaped cutting discs [5].

Zhang et al. (2018) investigated the wear of cutting disc rings using a cutting disc wear test. This experiment was conducted between cutting disc rings with six different hardness types and three different rock types using a Linear Cutting Machine (LCM). This research studied the mechanism and depth of wear using a laser microscope, and optimal cutting disc wear was determined by selecting the appropriate blade shape [6].

Pan et al. (2018) examined the effect of confinement stress on rock-cutting performance in TBM-cutting discs. The results showed that with increased confinement stress, fatigue indicators, and rock-cutting volume, initially increased but then decreased rapidly and significantly [7]. Su et al. (2020) investigated TBM cutting disc wear in hard rock in a metro tunneling project in Shenzhen, China. In this study, parameters such as uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), abrasion index (CAI), advance rate, and rotation speed were used [8]. Li et al. (2021) presented a new predictive model for vertical and lateral forces on discs based on the Roxborough and Phillips (1975) theoretical model, Rostami (1997) model and Osburn (1969) model [9]. Shen et al. (2022) emphasized the importance of investigating TBM cutting disc wear in tunnel boring machines. This study showed that about 23% of failures were due to abnormal wear, and the lateral cutting tool wear was much less than central tools, which differs from wear laws [10]. Li et al. (2022) investigated the effect of pre-cut groove depth on rock-breaking performance in TBM cutting discs. This research was conducted to improve tunnel boring machine performance in hard rocks. This study examined the effect of pre-cut groove depth on rock-breaking performance using full-scale linear cutting tests [11].

Rostamsowlat (2018) studied the impact of various cutting tool materials and cutting depth on rock cutting. The research demonstrated statistically significant findings, showing that both the physical properties of the tools and their cutting depth influence key performance metrics such as energy consumption and tool wear. This study provided detailed statistical analyses underscoring the importance of optimizing tool characteristics to enhance cutting efficiency [12].

Sarfarazi et al. (2022) examined the impact of single and twin tunnel configurations on collapse patterns and maximum ground movement. The research concluded that twin tunnels significantly alter collapse patterns and can induce greater ground movement compared to single tunnels. Their analysis demonstrated that the spatial arrangement and proximity of twin tunnels are critical factors influencing surrounding ground stability. The study provided statistical evidence supporting the hypothesis that careful planning and design are essential for minimizing adverse effects in tunnel construction projects [13].

Ansari et al. (2023) found an appropriate method for studying tool wear in soft ground by examining the impact of various soil particle size parameters on cutting tool wear in mechanized tunneling using EPB-TBM machines. Their studies showed that tool wear increases with an increase in D_{10}, D_{30} and D_{60} values and effective size in soils with more than 10% fine particles [14]. Amoun el al. (2023) developed a simulator for a tunnel-boring machine (TBM) to assess how various factors influence wear on cutting tools. They discovered that tools wear out more slowly in coarse-grained soils compared to fine-grained soils. Additionally, their findings suggest that soil's silt and clay composition affect particle size distribution. They noted a potential reduction in tool wear and torque by 58% and 34%, respectively, when using suitable excavated materials [15]. Mousapour et al. (2023) explored cutting tool wear through a lab simulation of a TBM. Their results indicated that decreasing the cutter head's rotational speed from 35 to 10 rpm could lessen tool wear by as much as 63%. Moreover, shortening the excavation duration from 80 to 10 minutes could decrease tool wear by up to 58%. They also observed that tool wear escalates with moisture levels up to 10%, but declines as moisture increases from 10% to 25% [16].

Tabrizi et al. (2023) investigated cutting tool wear in soft soil using a new tunnel-boring machine simulator. The resistance of cutting tools to wear is one of the most critical factors in the efficiency of Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs). By studying wear at different densities and moisture percentages, a decreasing trend in wear with similar conditions was observed at higher moisture percentages. The results of this study showed that increasing penetration rate and cutter head rotation speed could respectively lead to a decrease and increase in cutting tool wear [17]. Luo et al. (2023) examined rock cutting using a water jet disc-cutting machine. In this research, the effect of water jet base depth and cutting distance on the performance of the disc cutting machine was investigated. The results showed that with the increase in the depth of water jet base, the cutting disc forces decreases. The combination of the optimal cutting distance and water jet base depth was also determined to improve rock-cutting efficiency [18]. Wang et al. (2023) presented a predictive model for penetration rate in tunneling using a full-scale linear cutting test and machine learning algorithm. This model is a semi-theoretical model based on full-scale linear cutting tests [19].

Fu et al. (2023) examined rock fracturing at the face of jointed tunnel ground when using a Tunnel Boring Machine (TBM), integrating both experimental and numerical methodologies. The researchers conducted a series of experiments simulating TBM operations, providing valuable insights into the mechanical behavior and fracturing processes of rock. Their numerical analysis confirmed the experimental findings, showing a strong correlation between predicted and observed fracture patterns. Statistical analysis identified key factors influencing rock fracturing, such as joint orientation and spacing, which are crucial for optimizing TBM performance and tunneling efficiency [20].

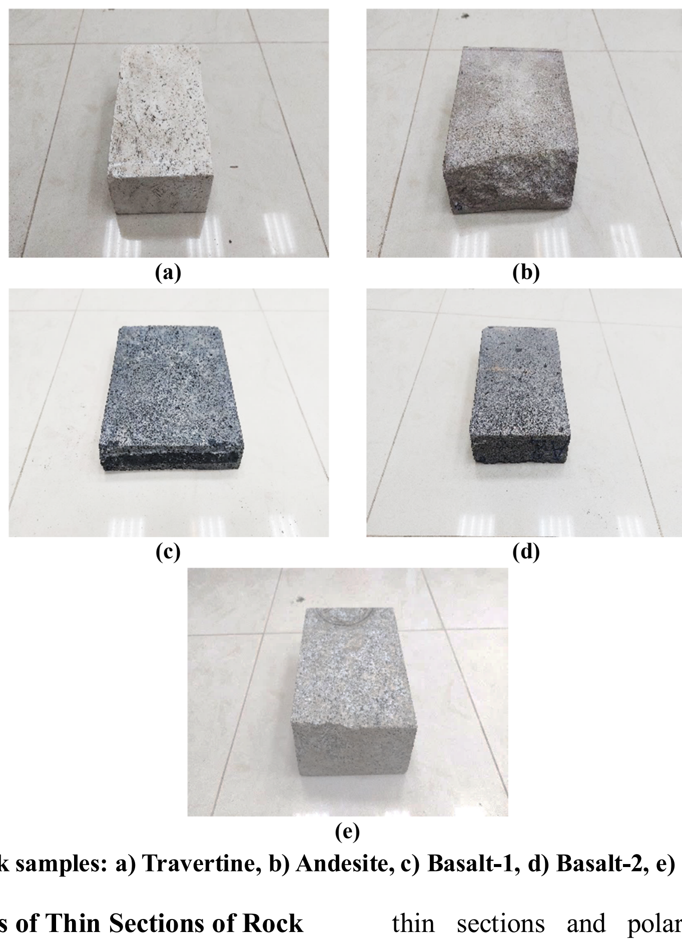
Ardalanzdeh (2024) investigated the effects of mineral size, texture coefficient (TC), and ductility-brittleness on hole creation in granitic rock specimens. The researchers found that larger mineral sizes and higher texture coefficients significantly improved the ease and efficiency of hole creation, with brittle minerals yielding better drilling performance. Statistical analysis revealed a strong correlation between the texture coefficient and drilling performance, emphasizing TC as a key predictor of drilling outcomes. The study emphasized the importance of these geological characteristics in optimizing drilling techniques for granitic formations [21].

In this study, while constructing a small-scale LCM linear cutting device, the effect of the wear of the cutting tool on the efficiency of rock cutting and its comparison in a V-shaped cutting disc was performed. This work introduces a novel small-scale Linear Cutting Machine (LCM) that facilitates detailed and economical laboratory testing of rock cuttability and tool wear—an approach not extensively adopted in existing studies. This study extends our investigation to a comprehensive analysis of a wide array of both mechanical and mineralogical rock properties, providing a deeper understanding of their impact on tool wear. Additionally, we integrate microscopic studies before cutting tests, offering crucial insights into the microstructural characteristics that influence cutting tool wear—an aspect that has often been overlooked in previous research. This study uniquely analyzes the effects of various penetration depths on tool wear across different rock types, providing new data for optimizing cutting parameters in TBM operations. The primary objective of this study is to examine how the mechanical properties of rocks influence cutting tool wear using a novel small-scale Linear Cutting Machine (LCM). Small scale linear cutting laboratory tests were conducted on 5 rock samples with different geological sources. In studies conducted to date, the cutting disc at various penetration depths has always faced an intact and undisturbed rock surface. One of the crucial innovations of this study is the preservation of excavation continuity in the laboratory tests performed. This research aims to:1- Determine the correlation between various rock mechanical properties (such as uniaxial compressive strength, Brazilian tensile strength, and abrasiveness) and the wear rate of disc cutters. 2- Assess the performance of disc cutters across different rock types using a newly developed small-scale LCM, which allows for more controlled and repeatable laboratory conditions. 3- Explore the relationship between penetration depth and cutter wear, thereby providing insights that could enhance the design and efficiency of tunnel boring machines in various geological settings.

2. Properties of Samples in Laboratory Linear Cutting Tests

In the present work, samples of rocks from various geological sources were used to investigate the abrasion of cutting discs. The prepared samples include travertine (chemical sedimentary), andesite (volcanic igneous), low and high porosity basalts (mafic volcanic igneous), and quartz syenite (felsic plutonic igneous) rocks (Figure 1). The travertine and basalt rocks are from mines in Nir county, Ardabil province, the andesite rock is from mines in Tabriz city, and the quartz syenite rock is from mines in Ahar county, East Azerbaijan province. In the selection of rock samples for this study, particular attention was given to rocks that are commonly encountered in engineering projects. The chosen samples, while similar in mechanical properties, offer a controlled baseline for assessing tool wear under consistent conditions.

In this work, the dimensions of the rock samples were 200 mm × 150 mm × 80 mm, respectively, with the thickness of the basalt-1 and basalt-2 rock samples set at 40 mm. Uniaxial compressive strength, tensile strength, and modulus of elasticity tests were conducted on the rock samples, according to ASTM D7012-21 for the compressive strength and modulus of elasticity methods, and ASTM D3148-22 for the measurement of elastic constants by ultrasonic velocity measurements. These tests aimed to investigate the mechanical properties of the rocks and their influence on abrasion resistance. The results obtained from these tests are presented in Table 1 [22-23].



(a) (b) (c) (d) (e)

Figure 1. Rock samples: a) Travertine, b) Andesite, c) Basalt-1, d) Basalt-2, e) Quartz syenite.

3. Microscopic Studies of Thin Sections of Rock Samples

To properly identify and analyze small minerals and rocks that are indiscernible in hand samples, thin sections and polarizing microscopes are essential. These microscopes not only magnify rock components but also reveal their optical properties under different lighting conditions, such as parallel, cross, and convergent polarized light. Additionally, they are equipped with digital cameras for capturing detailed images.

In addition to microscopic analysis, petrography laboratories perform macroscopic evaluations of hand samples, including color analysis, hardness testing using the Mohs scale, and acid tests to detect carbonates. Figure 2 illustrates the method of analyzing rock samples in microscopic studies. Additionally, Figure 3 describes the microscopic characteristics of the rock samples in this work.

Table 1. Mechanical properties of the rock samples in the present work.

No.	Rock Type	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	Elastic modulus (GPa)
1	Travertine	38.50	4.279	7.7
2	Andesite	41.80	5.62	13.7
3	Basalt-1	48.28	7.274	16.2
4	Basalt-2	58.90	7.10	17.6
5	Quartz syenite	75.92	6.20	34.9

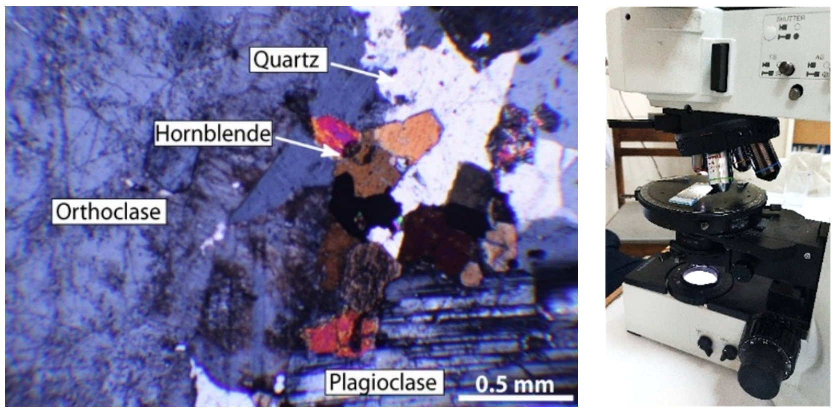
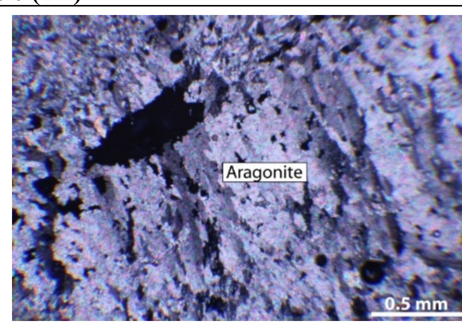


Figure 2. Method of analyzing rock samples in microscopic studies.

Travertine sample (TR)

Rock Type	Travertine
Main minerals	Aragonite
Secondary minerals	-
Percentage of minerals	Aragonite (90 %)
Texture	Crystalline and porous texture
Porosity	About 10 %
Crystal size	Coarse to fine crystal
Impregnation	No



Andesite sample (AN)

Rock Type	Pyroxene andesite
Main minerals	Pyroxene and plagioclase
Secondary minerals	Hornblende, biotite, olivine, opec minerals, calcite, biotite and apatite
Percentage of minerals	Pyroxene (25%) and plagioclase (50 %)
Texture	Porphyry and hollow rock texture can also be seen
Porosity	About 5 %
Crystal size	Coarse to fine crystal
Impregnation	No

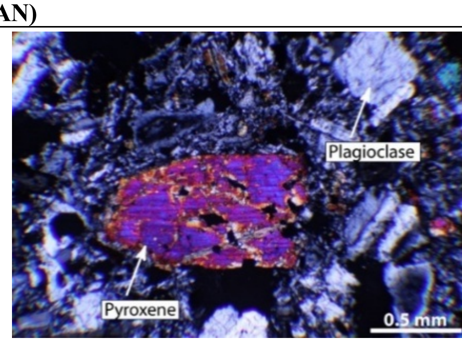
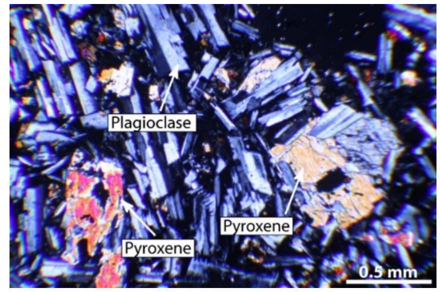
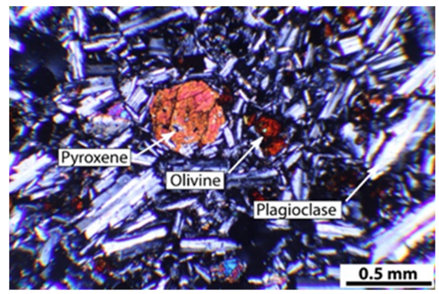


Figure 3. Microscopic characteristics of the studied rock samples.

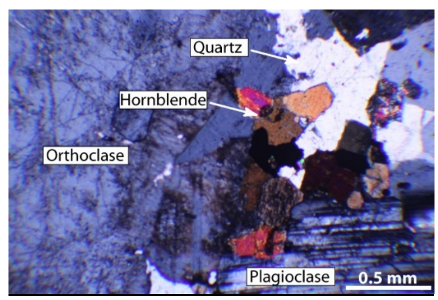
Basalt sample-type 1 (BA-1)	
Rock Type	Basalt
Main minerals	Feldspar (plagioclase), pyroxene (clino and orthopyroxene), olivine (fragmented)
Secondary minerals	OPEC minerals
Percentage of minerals	Feldspar (plagioclase) (50%), pyroxene (clino and orthopyroxene) (25%), olivine (fragmented) (10%)
Texture	Porphyry, aphanitic, and porphyritic microlithic textures are observed
Porosity	very porous
Crystal size	microcrystal
Impregnation	No



Basalt sample-type 2 (BA-2)	
Rock Type	Basalt
Main minerals	Feldspar (plagioclase), pyroxene (clinopyroxene)
Secondary minerals	Olivine (degraded), OPEC minerals
Percentage of minerals	Feldspar (plagioclase) (50%), pyroxene (clinopyroxene) (25%)
Texture	The microlithic rock texture is porphyric and porous
Porosity	Porous
Crystal size	Fine and coarse crystal
Impregnation	No



Granite sample (GR)	
Rock Type	Quartz syenite
Main minerals	Alkali feldspar (orthoclase), plagioclase
Secondary minerals	Quartz, biotite, amphibole, calcite, clay minerals, opac minerals, muscovite, epidote, apatite and zircon
Percentage of minerals	Alkali feldspar (orthoclase) (50%) and plagioclase (30%)
Texture	Granular hydromorphic hip tissue
Porosity	Does not have
Crystal size	Coarse crystal
Impregnation	No



Continuous of Figure 3. Microscopic characteristics of the studied rock samples.

4. Equivalent Quartz Content (EQC)

The Equivalent Quartz Content (EQC) is determined using a formula that calculates the weighted average of the hardness values of the constituent minerals, according to their volumetric proportions within the rock sample. The formula given in **Equations 1** as follows:

$$EQC = \sum V_i \times H_i \tag{1}$$

Where are:

V_i – Volumetric percentage of each mineral,

H_i – hardness factor.

The equivalent quartz content is recognized as one of the essential parameters in studying rock hardness. Each type of mineral present in a rock sample can have a different impact on the final hardness of the sample based on the Mohs hardness scale. Table 2 presents the Mohs hardness values and equivalent quartz content of the rock samples in the current study.

5. Introduction to Small-Scale Linear Cutting Machine (LCM)

Rock samples along tunnel lines can be extracted in the identification stages or before the construction of tunnel branches and transferred to the laboratory. Then, using full-scale linear or rotational cutting machines, sets of cutting tests can be conducted on the samples known for evaluating the rock's cuttability. LCM and RCM tests on a full scale can be a suitable guide for designing full-face TBM excavation machines. They can also encompass a wide range of cutting forces and settings, effectively eliminating the range of influence. Additionally, these tests reduce uncertainties in the unusual cutting behavior of rocks. In other words, LCM and RCM tests on a full scale are reliable and trustworthy. The results of laboratory tests can directly be used to evaluate the performance of full-face TBM excavation machine designs in real conditions. For this reason, many research studies have been conducted based on the results of LCM and RCM tests.

Table 2. Values of Mohs hardness and equivalent quartz content of rock samples

No.	Rock Type	Main minerals	Volume (%)	Mohs hardness	Equivalent quartz content (%)
1	Travertine	Aragonite	90	3.5	45
2	Andesite	Plagioclase	50	6	62.5
3	Basalt-1	Pyroxene	25	5.5	71.8
4	Basalt-2	plagioclase	50	6	62.5
5	Quartz syenite	pyroxene	25	5.5	68.6

5.1. Components of the small-scale linear designed cutting machine

In this study, to investigate the effect of cutting tool wear on rock cutting efficiency and compare it in a V-shaped cutting disc, a small-scale linear cutting machine was built in the mechanized excavation laboratory of Sahand University of Technology. Then, linear cutting experimental tests were performed on 5 different rock samples. The structure of the small-scale linear cutting machine consists of four main parts, each of which is divided into smaller components. These main parts include:

- Dynamometer: this structure can excavate rocks and record cutting forces.
- Hydraulic cylinder: hydraulic cylinder was used to simulate rock excavation penetration depths.
- Pneumatic cylinder: pneumatic cylinder was used for excavation in rocks.
- Box: used for holding and moving rocks towards the cutting disc for excavating and collecting excavation debris.

A 3D schematic of the small-scale linear cutting machine designed is shown in Figure 4.

The small-scale linear cutting machine designed and manufactured consists of several essential components: 1- Penetration depth-adjusting cylinder, 2- Jack cylinder for setting rock position to excavation, 3- Rock sample box, 4- Air compressor, 5- Hydraulic manual pump, 6- Compressed air control system, 7- Dynamometer for recording cutting forces, 8- Data logger and 9- Linear cutting machine software. A dedicated data logger device and specialized software for recording cutting forces have been designed and built for this machine. Figure 5 shows a complete view of the small-scale linear cutting machine constructed in the mechanized excavation laboratory of Sahand University of Technology.

In previous studies, the cutting disc has interacted with rocks at various penetration depths with intact and untouched surfaces. Consequently, vertical forces, tangential forces, specific energy, etc., were obtained for the uncut rock section. This critical issue eliminates the excavation continuity effect.

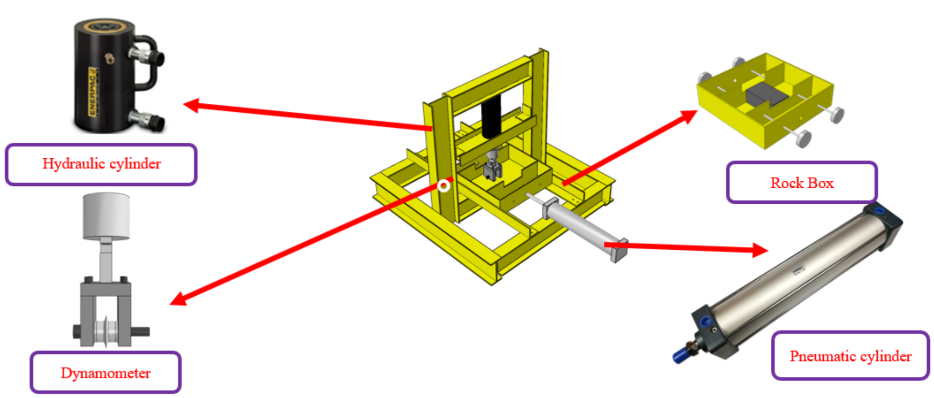


Figure 4. 3D schematic of the designed small-scale linear cutting material.

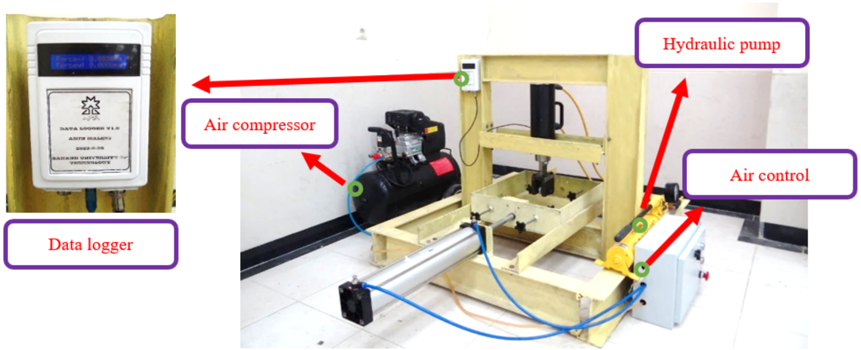


Figure 5. The full view of the small-scale linear cutting machine in the mechanized excavation laboratory of Sahand University of Technology.

Excavation continuity is crucial in full-face TBM machines, where cutting discs penetrate a few centimeters into the rock. Then, excavation proceeded smoothly with the rotation of the TBM cutter head; it was decided that excavation continuity should be considered in this study. Therefore, in the performed laboratory tests, the cutting disc initially penetrated 1 mm into the rock, and then, after excavating a length of 2.2 m in the rock, an additional 0.5 mm penetration depth was added to the cutting disc. Hence, the penetration depth in three stages is 1 mm, 1.5 mm, and 2 mm, with the cutting disc passing from the location of the previous excavation place in all penetration depths. As a result, excavation continuity can be maintained for five different rock samples.

Considering that there are numerous cutting discs in the TBM cutter head and due to the different distances from the center of the cutter head and sometimes angles they have, various wear occurs on them. Therefore, in this study, a middle-cutting disc was selected, and its wear was examined. The cutting disc studied in this research is located 3.5 m away from the center of the cutter head. This cutting disc covers a distance of 22 m in each rotation of the TBM cutter head, considering the circle's circumference. Considering scale conversion of 1:10 in this study, the manufactured cutting disc should be moved 2.2 m on the rock. The rocks prepared for LCM testing have a length of 20 cm, so the manufactured cutting disc should cover 11 lines with a spacing of 1 cm at each penetration depth. Figure 6 illustrates the procedure for conducting laboratory tests in this study.

Figure 6. The steps of performing the LCM test.

6. Evaluating Cutting Disc Wear in Small-Scale Linear Cutting Machine at Different Penetration Depths

Cutting disc wear refers to the gradual deterioration and damage to the surface of the cutting disc due to repeated use. Various factors can cause this wear and significantly impact the cutting disc's efficiency in the tunneling process. Factors that can lead to wear of cutting disc include:

1. Rock type: hardness and type of rock significantly impact the disc's wear. Harder rocks wear out cutting tools faster.
2. Disc design: The design of the cutting disc, including the material, shape and size, number, and arrangement of cutting tools, and other features, can affect disc wear.
3. Disc rotation speed: The rotation speed of the cutting disc can also impact its wear. Increasing the rotation speed may increase disc wear.

Cutting disc wear can reduce the efficiency of TBM excavation machines and consequently increase costs and excavation time. Regular maintenance, timely repairs, and the use of high-quality discs are crucial for extending the useful life of the cutting disc and improving its performance. The results of cutting disc wear at different penetration depths show that as the penetration depth increases, the values of cutting disc wear also increase for all types of rocks. The main reason is that with increased penetration depth, the contact area between the cutting disc and the rock also increases, leading to higher friction, heat generation, and increased interference between the cutting disc and the rock's pores and joints. The highest amount of cutting disc wear is related to basalt-2 rock, and the lowest amount is associated with travertine rock. Table 3 shows the average wear of cutting disc for different rock samples at various penetration depths. Figure 7 also illustrates the average wear of cutting discs in laboratory tests.

Table 3. Average wear of cutting disc of the small-scale linear cutting machine for different rock samples at different penetration depths.

No.	Rock Type	Disc initial weight (g)	Disc weight in penetration 2 mm (g)	The total mass of excavated rock chips (g)	Average wear of cutting discs (mm)
1	Travertine	198.352	198.308	2.023	0.35
2	Andesite	201.009	200.973	3.590	0.74
3	Basalt-1	200.227	200.130	0.877	1.58
4	Basalt-2	200.188	200.153	3.643	1.83
5	Quartz syenite	202.061	202.032	1.708	1.35

7. Investigation of Rock and Blade Interaction Using a Small-Scale Linear Cutting Machine

In mechanized excavation, tools (blades or cutters) are divided into two main categories: scratch blades and gouging blades. Each tool is selected based on the specific ground conditions, rock properties, and machine type. Therefore, understanding the relationship between rock properties and the appropriate and optimal blade selection is vital. The properties of the rock have a significant impact on the choice of cutters or blades. These properties include rock strength (compressive and tensile), hardness and toughness of the rock, its encompassing minerals, rock texture, grain size and shape, and its plastic behavior or deformability.

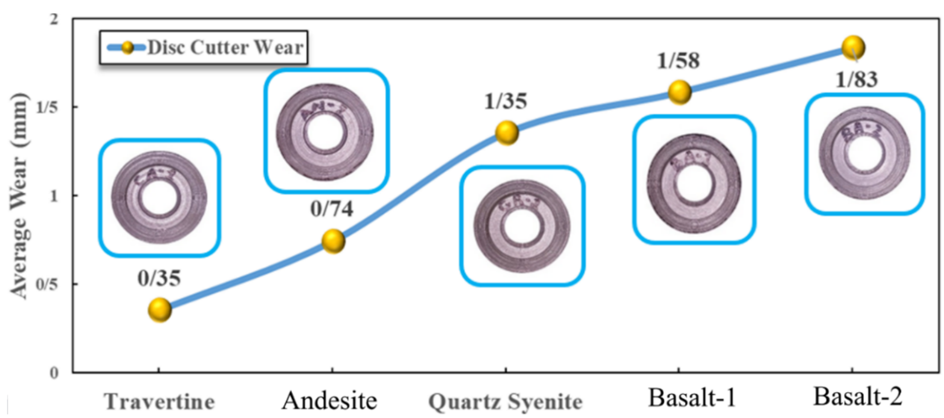


Figure 7. Average wear of cutting disc of the small-scale linear cutting machine in different rock samples.

Typically, several rock mechanical tests are conducted, including uniaxial compressive strength tests, indirect tensile strength tests (Brazilian), equivalent quartz content (EQC), and elastic modulus (Young's modulus and Poisson's ratio) to describe the type of rock and its potential behavior in excavation and fracture analysis. To make successful tool selections, measuring some of these properties is essential. This section examines and analyzes results obtained from laboratory-scale linear cutting tests.

7.1. The Effect of Uniaxial Compressive Strength of Rocks on Disc Cutter Wear

Uniaxial compressive strength test is one of the important and common tests used to study and determine the mechanical properties of rocks. The results of this test can be used for various purposes, such as assessing blasting, determining excavation machine specifications, etc. Additionally, uniaxial compressive strength is used as a primary factor for classifying types of rocks, and information obtained from this test can aid in better classification and understanding of rocks and their characteristics. The study of results obtained from disc cutter wear in 5 different rock samples in this study using a small-scale linear cutting machine shows that with an increase in uniaxial compressive strength of rocks, disc cutter wear values also increase (Figure 8). According to Table 1, the lowest uniaxial compressive strength value corresponds to travertine rock, while the highest value belongs to quartz syenite rock. As shown in Figure 8, the disc cutter wear in quartz syenite (with the highest uniaxial compressive strength value) is less than that of the disc cutter wear in basalt-2. Both basalt-2 and quartz syenite rocks are considered hard igneous rocks. The main difference between these two types of rocks lies in their textures. Basalt-2 has a porphyritic aphanitic texture, while quartz syenite has a hypidiomorphic granular texture. Therefore, basalt-2 rock has lower uniaxial compressive strength than quartz syenite rock. Still, its high porosity, joints, and fine crystals create more wear on disc cutters than quartz syenite rock. Based on the results obtained, it can be inferred that the uniaxial compressive strength of rocks can indicate the wear trend on disc cutters but cannot fully predict the wear that occurs on them. According to the results shown in Figure 8, there is a linear relationship between uniaxial compressive strength values of rocks and disc cutter wear with a coefficient of determination of 0.64. Therefore, the parameter of uniaxial compressive strength of rocks is an important relative parameter for determining the disc cutter wear index.

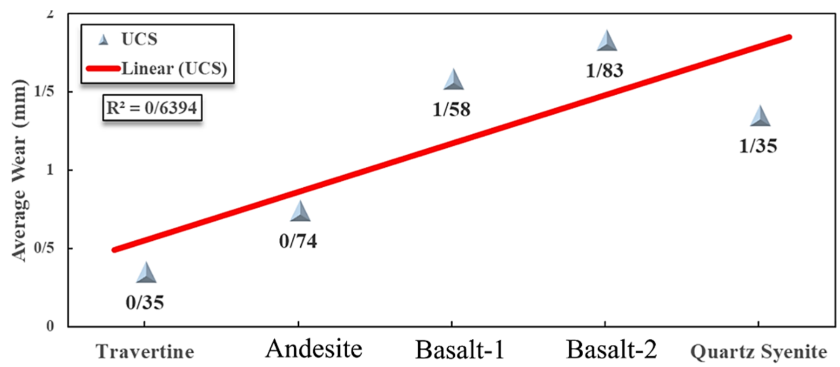


Figure 8. Changes in disc cutter wear according to the uniaxial compressive strength of rocks in 5 different rock samples.

7.2. The Effect of Brazilian Tensile Strength of Rocks on Disc Cutter Wear

Brazilian tensile strength test aims to measure the tensile strength of prepared rock samples indirectly. Based on experimental evidence, in biaxial stress fields, when one principal stress is tensile and the other principal stress is compressive and less than three times the principal tensile stress, most rocks fail in tension and in their unconfined tensile strength. Examining results obtained from disc cutter wear in 5 different rock samples in this study using a small-scale linear cutting machine shows that with an increase in the Brazilian tensile strength of rocks, disc cutter wear values also increase (Figure 9). According to Table 1, the lowest Brazilian tensile strength value corresponds to travertine rock, while the highest value belongs to basalt-1 rock. As shown in Figure 9, only the wear value in basalt-1 rock, which has the highest Brazilian tensile strength value, is lower than that of basalt-2 rock. Both basalt rocks used in this study are sourced from a geological area. They are very similar in mineralogical characteristics, with the only difference being their textures, where basalt-1 is more porous than basalt-2. The reason for selecting these two basalt rocks in this study is to investigate the effect of porosity on disc cutter wear. Basalt-1, due to the presence of minerals with high hardnesses compared to basalt-2, has a higher Brazilian tensile strength, but less wear on disc cutters used in basalt-1 rock compared to disc cutters in basalt-2 rock has occurred. The reason for this difference in wear in these two types of rocks is the difference in crystal size in the two types of basalt. Basalt-2 consists of a combination of coarse and fine crystals, creating a denser texture compared to basalt-1. Therefore, the Brazilian tensile strength of rocks can indicate the wear trend on disc cutters but cannot fully predict the wear that occurs on disc cutters. Additionally, based on Figure 9, it can be inferred that there is a linear relationship between Brazilian tensile strength values of rocks and disc cutter wear with a coefficient of determination of 0.84. Thus the Brazilian tensile strength of rocks is an important relative parameter for determining the disc cutter wear index.

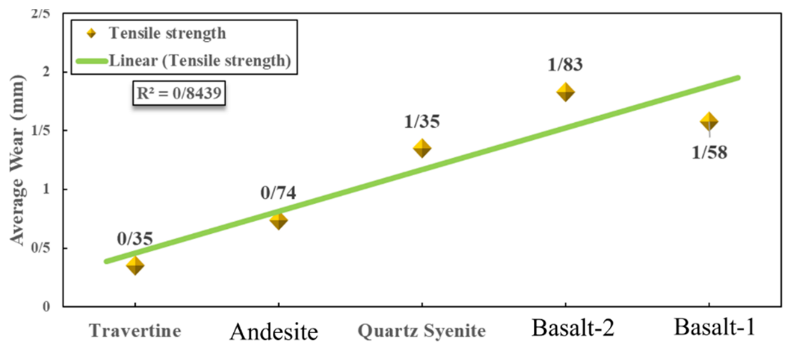


Figure 9. Changes in disc cutter wear according to Brazilian tensile strength in 5 different rock samples.

7.3. The Effect of Equivalent Quartz Content (EQC) of Rocks on Disc Cutter Wear

Equivalent quartz content is known as one of the important parameters in studying rocks' abrasiveness. Each type of mineral present in a rock sample can have a different effect on the abrasiveness of the sample according to hardness of the Mohs scale. Table 2 describes the values of Mohs hardness and equivalent quartz content of rock samples of present study. The lowest equivalent quartz content corresponds to travertine rock, while the highest is basalt-1. Examining results obtained from disc cutter wear in 5 rock samples using a small-scale linear cutting machine shows that with an increase in equivalent quartz content of rocks, disc cutter wear values also increase (Figure 10). As shown in Figure 10, only the wear value in basalt-2 is higher than quartz syenite (due to the lower porosity of quartz syenite) and basalt-1 (due to denser crystals in basalt-2). Therefore, the equivalent quartz content of rocks can indicate the wear trend on disc cutters but cannot fully predict the wear that occurs on disc cutters. Based on the results of Figure 10, it can be inferred that there is a linear relationship between equivalent quartz content values and disc cutter wear with a coefficient of determination of 0.63. Thus equivalent quartz content is an essential relative parameter for determining the disc cutter wear index.

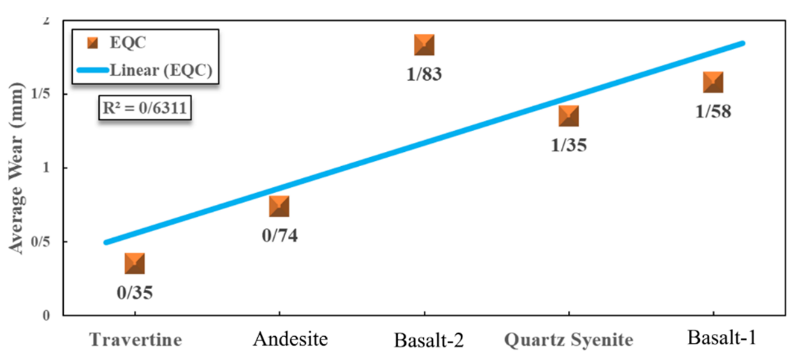


Figure 10. Changes in disc cutter wear regarding equivalent quartz content (EQC) in 5 different rock samples.

7.4. The Effect of Rock Elastic Modulus on Disc Cutter Wear

Elastic modulus is the ratio of stress to strain in elastic solid materials below the yield strength, where Hooke's Law is valid, and the modulus of elasticity is constant. The rock elastic modulus, similar to strength, can be static or dynamic depending on the applied load rate. The dynamic modulus of elasticity is greater than the static modulus, but as the rock has higher strength, these two values become closer. The dynamic modulus of elasticity depends on factors such as wave propagation speed, rock type, texture, density, porosity, applied stress, water content, etc. Young's modulus also depends on factors like temperature, loading rate, type of test, etc.

The investigation of the results obtained from cutting disc wear in 5 different rock samples of this study using a small-scale linear cutting machine shows that with an increase in the value of the rock tangent elastic modulus, the values of cutting disc wear also increase (Figure 11). According to Table 1, the lowest elastic modulus value corresponds to travertine, and the highest value belongs to quartz syenite. As shown in Figure 11, only the cutting wear value in quartz syenite with a higher elastic modulus is lower than that in basalt-2. The two parameters of uniaxial compressive strength and rock tangent elastic modulus show similar results due to the same loading conditions. In this section, the main difference between these rocks is their texture; basalt-2 has an aphanitic porphyritic texture, while quartz syenite has a hypidiomorphic granular texture. Therefore, basalt-2 has a lower elastic modulus than quartz syenite, but its highly porous and jointed nature creates more wear on cutting discs than quartz syenite. Hence, determining the rock elastic modulus can indicate the wear trend on cutting discs but cannot fully predict the wear that occurs on cutting discs. Based on the results from Figure 11, it can be inferred that there is a linear relationship between elastic modulus values and cutting disc wear with a determination coefficient of 0.64, and the elastic modulus is an essential relative parameter for determining cutting disc wear index.

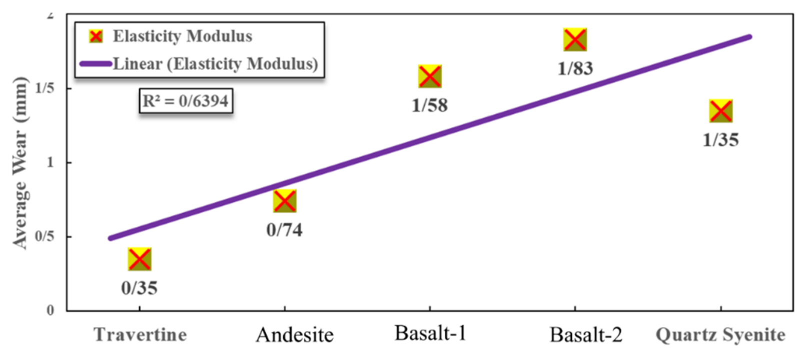


Figure 11. Changes in the wear of the disc cutter according to the values of the modulus of elasticity in 5 different rock samples.

8. Discussion and Comparison of Characteristics and Results of Small-Scale Linear Cutting Machine in this Study with Previous Studies

In this study, the influence of physical and mechanical characteristics of rocks on the wear of cutting tools in excavation machines has been investigated using a new small-scale linear cutting machine (LCM). Through the conducted examinations on the mechanical properties of 5 different rock samples and cutting disc wear, it can be concluded that cutting disc wear is not solely dependent on a specific factor but somewhat influenced by various factors such as alloy, geometry, and dimensions of cutting discs, physical and mechanical characteristics of rocks, constituent minerals, and excavation method.

8.1. Size, Geometry, and Alloy of Disc Cutters

In many previous studies, different cutting discs with varying alloys and geometries have been used to determine the wear values of cutting discs. In study of the linear cutting machine test conducted by Tumac and Balci (2015), two types of different cutting discs with diameters of 330 mm (with a tip width of 12 mm) and 432 mm (with a tip width of 18 mm) were used for linear cutting tests. In this study, the geometry type of the cutting discs is Constant Cross-Section (CCS), and the alloy of the cutting discs is not specified. In the study by Zhang et al. (2018); to simplify the LCM linear cutting test, a small-scale cutting disc ring with a diameter of 140 mm and a width of 5 mm was used instead of a full-scale cutting disc ring. The cutting disc rings are made of H13 steel. Six cutting disc rings with different hardness and toughness were prepared through annealing and quenching for linear cutting tests. In the study by Zhu et al. (2022), the linear cutting machine has a cutting disc with a constant cross-section (CCS). The radius of the cutting disc is 216 mm, and the blade thickness is 20 mm. The alloy of the cutting disc is not mentioned in this study. In the studies by Pan et al. (2018), Li et al. (2022), and Wang et al. (2023), a constant cross-section (CCS) 17-inch cutting disc (diameter 432 mm, tip width 15 mm) was used. Therefore, in the studies conducted so far, the alloy of the cutting discs has not been specified. Based on past studies, it can be inferred that there is no standard for the alloy, geometry of the cutting disc ring, and scale of cutting discs used in linear cutting tests (LCM). The present study used cutting discs with a small scale of 56 mm, VCS geometry, and AISI4140 alloy.

8.2. Equivalent Quartz Content

Another important topic in LCM linear cutting tests is using rocks with different geological sources. In many studies conducted to date, including Zhang et al. (2018), Pan et al. (2018), Li et al. (2022), Zhu et al. (2022), Lu et al. (2023), and Wang et al. (2023), microscopic studies to examine mineralogy have not been conducted. The necessity of conducting microscopic studies is because two identical rocks but with different genesis in terms of mineralogy and equivalent quartz content are different from each other and this issue has an important effect on the wear of cutting discs. Therefore, conducting thin-section studies before performing LCM linear cutting tests is crucial. This study undertook thin-section studies before LCM linear cutting tests for better examination, and the impact of equivalent quartz content on cutting disc wear was studied.

8.3. Type and Dimensions of Rock Samples

Previous studies used various rock samples with different geological sources and dimensions to conduct linear cutting tests. For example, in the study by Li et al. (2022), only the granite was used for linear cutting tests. The rock samples in this study were 1000 mm × 1000 mm × 600 mm. Additionally, in the study by Shu et al. (2022), C30 concrete was used as a test material for linear cutting tests. The concrete samples in this study were 850 mm × 800 mm × 300 mm. In the study by Lu et al. (2023), a granite rock sample was used as a hard rock sample for linear cutting tests. The granite was cut into rectangular cubes with dimensions of 900 mm × 380 mm × 280 mm to fit inside a steel box. Therefore, in most of the past important studies, only one type of rock has been used for conducting linear cutting tests. Additionally, the dimensions of rock samples in different studies are not consistent. The present study used five types of rocks with igneous, sedimentary, and metamorphic origins for LCM linear cutting tests. The dimensions of the rock samples in this study are 200 mm × 150 mm × 80 mm.

8.4. Comparison of the Method of Conducting LCM Tests in Past and Present Studies

Another critical topic is the method of conducting linear cutting tests. Various methods have been designed and implemented for conducting linear cutting tests using cutting disc rings in excavation machines, and some examples of these will be mentioned:

8.4.1. Normal and Tangential Force Examination by Tomak and Balci (2015)

Tumack and Balci (2015) developed a new model for predicting normal and tangential forces on CCS-type cutting disc rings by modifying the empirical model of Bilgin (1977) designed for V-shaped disc cutters and based on the theoretical model developed by Roxborough and Phillips. This study used linear cutting tests to estimate normal and tangential forces. The linear cutting tests in this study involve variable penetration of the cutting tool from 3 to 12 mm, and the spacing of the cutting lines is 70, 75, and 80 mm. The revised model showed improved predictions of normal and tangential forces compared to the original Bilgin model. The findings indicated significant variations in force measurements due to changes in penetration depth and line spacing, which are critical for optimizing cutting operations in terms of efficiency and tool wear.

By integrating the empirical data from Tumac and Balci's tests with the theoretical insights of Roxborough and Phillips, along with the foundational work of Bilgin, the field can advance toward more accurate and universally applicable predictive models for various cutting tools used in mining and construction. This comprehensive approach not only enhances the accuracy of force predictions but also improves the design and operational strategies for cutting equipment.

8.4.2. Lateral Stress Wxamination by Pan et al. (2018)

Pan et al. (2018) studied the effect of lateral stresses on the cutting efficiency of TBM cutting discs. This study compared the results of linear cutting tests on a full scale under different lateral stress conditions in sandstone and granite. The method of conducting LCM linear cutting tests involves uniform spacing of cutting disc rings at 80 mm because TBMs usually work in hard rocks at a cutting distance of about 76 mm (usually between 60 to 90 mm) with a depth of penetration per revolution as much as the power of the machine allows. The range of penetration depth of cutting disc rings in this study was determined based on rock strength, disc cutter force, and rock fracturing phenomenon.

In our research, we conducted small-scale linear cutting tests with uniform disc spacing and penetration depth, specifically chosen based on the geological and mechanical characteristics of a diverse set of rock types. This approach allowed us to meticulously control and replicate test conditions, ensuring consistency and accuracy in evaluating cutting tool wear across different rock types, including travertine, andesite, basalt, and quartz syenite, beyond the sandstone and granite used by Pan et al. (2018). Furthermore, our study expands the examination of cutting disc wear to include not only the impact of rock strength and cutter force but also specific mineralogical properties, such as quartz content and abrasiveness, which directly influence the wear process. We observed that cutting disc wear increases with penetration depth and strongly correlates with Brazilian tensile strength and the mineralogical composition of rocks. This finding highlights the nuanced relationship between rock properties and cutting efficiency, complementing Pan et al.'s focus on lateral stress effects

8.4.3. Examination of the Influence of Disc Cutter Characteristics by Zhang et al. (2018)

Zhang et al. (2018) examined the wear characteristics of cutting disc rings with six different hardness levels using the LCM linear cutting machine. Generally, penetration is controlled at 8 mm in tunnel projects using TBM machines and cutting spacing at 80 mm. However, in these experiments, the radius of the cutting disc ring was 70 mm, the width of the cutting disc ring was 5 mm, and the cutter spacing for full utilization of rock samples was set at 15 mm. Therefore, in wear tests, the penetration of the cutting disc ring into the rock should be controlled to about 1 mm.

Our findings provide a detailed analysis of how varying rock types influence the wear and efficiency of cutting tools under controlled laboratory conditions. Unlike Zhang et al., who utilized a constant penetration depth and varied only the hardness of the cutting disc rings, our research varied penetration depth across different rock types while maintaining a consistent disc material to comprehensively understand the relationship between penetration depth and wear behavior. We observed that increasing penetration depth consistently led to greater wear across all tested rock types, including travertine, andesite, basalt, and quartz syenite. This pattern of increased wear with greater penetration depths aligns with the principles outlined by Zhang et al., reinforcing that operational parameters, such as cutter spacing and penetration depth, critically affect wear characteristics. Furthermore, our study expanded the examined parameters by exploring the role of rock properties, such as Brazilian tensile strength, uniaxial compressive strength, and mineralogical composition, with a particular focus on their correlation with cutting disc wear.

8.4.4. Investigation of Specific Energy (SE) by Zhu et al. (2022)

In TBM projects, properly adjusting the penetration depth of cutting tools is crucial for improving tunneling efficiency, but optimal penetration strategies are still lacking. TBM operators tend to adjust operational parameters to achieve maximum penetration, leading to severe wear on cutting discs during the excavation of hard rocks. Field observations indicate a high correlation between the penetration of cutting discs and Specific Energy (SE) in excavation.

Our study aligns with the broader framework established by Zhu et al., as we explore the impact of rock properties on cutting tool wear at various penetration depths using a novel small-scale Linear Cutting Machine (LCM).

In our research, we examined the relationship between the mechanical properties of rocks—specifically uniaxial compressive strength, Brazilian tensile strength, and mineralogical composition—and their effect on the wear of cutting discs at different penetration depths. Our findings indicate that as penetration depth increases, cutting disc wear also increases across all tested rock types. This aligns with the principle that deeper penetration depths generally require higher specific energy (SE) and lead to greater tool wear, particularly in harder rock types. Furthermore, our study provides detailed insights into the effectiveness of different penetration depths by evaluating their impact on tool wear under controlled laboratory conditions. This approach has enabled us to systematically evaluate how variations in rock properties influence the SE required for efficient cutting. Moreover, our findings support Zhu et al.'s observation that no single method of linear cutting testing can universally address all aspects of rock cutting. Each rock type and cutting condition may require specific adjustments to cutting parameters to optimize performance. Our research highlights the need for more detailed, rock-specific linear cutting tests that can provide direct data to inform TBM design and operation, potentially leading to the development of standardized approaches for measuring and predicting TBM performance across various geological conditions.

Based on the points mentioned in previous studies, it can be inferred that the linear cutting test has been used for specific purposes, and the methods of conducting each test differ. This difference is because a single method of linear cutting test cannot be used to examine all aspects of excavation in rocks using cutting discs. Therefore, it is necessary to study more research and methods, and the best methods according to the subject under investigation should be introduced as linear cutting test standards.

In this study, an attempt has been made to address many points that have not been previously examined. One of the significant innovations in this study is maintaining excavation continuity in the conducted laboratory tests, which has not been considered in past studies. Considering the topics discussed, it can be understood that many questions and challenges need to be studied and investigated.

Table 4 present the comparison of the method of conducting LCM tests in past and present studies.

Table 4. Comparison of the method

Study Reference	Year	Number of Rock Types	Rock Types Used	Key Focus of Study	Details on LCM Test Method
Zhang et al. (2018)	2018	3	Varied	Wear of cutting disc rings with different hardness types	Used a small-scale LCM with laser microscope for wear depth measurement
Pan et al. (2018)	2018	2	Sandstone, Granite	Influence of confining stress on rock cutting efficiency	Full-scale linear cutting tests, studying the effect of stress on cutting
Li et al. (2022)	2022	1	Granite	Effect of pre-groove depth on rock-breaking performance	Full-scale tests to improve TBM performance in hard rocks
Current Study	-	5	Travertine, Andesite, Basalts, Quartz Syenite	Impact of mechanical properties on cutting tool wear	Small-scale LCM tests, focused on detailed analysis of wear across different rock types and penetration depth

Tabke 5. Rock property and impact on cutting device wear

Rock Property	Description	Impact on Cutting Device Wear
Mineralogy and abrasiveness	High quartz content increases abrasiveness.	Increases wear due to the hardness of minerals like quartz.
Grain size and bonding strength	Size of the grains and the intergranular bonding strength.	Finer grains and stronger bonds increase resistance, causing more wear.
Rock toughness	Ability of the rock to absorb energy without fracturing.	Higher toughness requires more energy for cutting, increasing wear.
Porosity and density	Amount of void space in the rock and its overall density	Highly porous rocks may reduce wear due to easier cuttability; effects vary by mineral content.
Water content	Moisture content within the rock.	Can reduce rock strength and wear; may act as a lubricant, reducing friction.
Thermal properties	Thermal expansion coefficients and conductivity.	Influences thermal stresses during cutting, impacting wear especially at high speeds.
Microstructure features	Presence of fissures, joints, and layers.	Irregular features can lead to uneven wear and affect cutting efficiency.

9. Conclusions

Conducting laboratory tests such as linear cutting tests on rocks before selecting the type of machine and adjusting the blade on the cutter head is very important. In this study, while constructing a small-scale LCM linear cutting device, the impact of tool wear on rock cutting efficiency was investigated, and a comparison was made with V-shaped cutting discs. In previous studies, cutting discs at different penetration depths have always faced intact and undisturbed rock surfaces. One of the significant innovations in this study is maintaining excavation continuity during laboratory tests. The innovations and most important results obtained from this study include:

1. Based on previous studies, it can be inferred that standards for alloy, cutter disc ring geometry, and the scale of cutting discs used in LCM linear cutting tests have not been introduced. This study used uniquely scaled 56 mm cutting discs with VCS geometry and AISI4140 alloy. Our results demonstrate that increases in penetration depth consistently lead to increased wear across all rock types tested. This is in line with the established understanding that deeper penetration requires higher specific energy and results in greater tool wear. Furthermore, we found that the mechanical properties of rocks, particularly Brazilian tensile strength, show a strong correlation with the wear rates of cutting discs. This suggests that Brazilian tensile strength could be a critical factor in predicting tool wear in TBM operations.

2. In many studies conducted to date, microscopic studies to examine the mineralogy of rocks have not been performed. Conducting thin section studies before conducting LCM linear cutting tests is essential. This study conducted thin section studies before LCM linear cutting tests to better understand the effect of equivalent quartz content on cutting disc wear. By integrating the insights from our research with the findings from studies like those of Pan et al. (2018), Zhang et al. (2018), and Zhu et al. (2022), we underline the necessity of considering both tool characteristics and rock properties in the design and operation of TBMs. Our study supports the notion that no single method of linear cutting test can universally address all aspects of excavation in rocks, highlighting the need for tailored testing approaches based on specific project conditions.
3. In most previous studies, a limited variety of rocks and different dimensions of rock samples haven used for conducting linear cutting tests. This study used five types of rocks with origins in igneous, sedimentary, and metamorphic sources in LCM linear cutting tests.
4. The purpose of microscopic studies and determining the equivalent quartz content for all rock samples is to examine the presence of minerals with high Mohs hardness and determine other rock properties such as texture, crystal size, and porosity. After microscopic studies and determining the equivalent quartz content of the rock, it can be understood that the equivalent quartz content can effectively predict cutting disc wear.
5. Based on the findings of this research, it can be understood that Brazilian tensile strength shows a better correlation with cutting disc wear values among the essential mechanical properties of the examined rocks. Additionally, parameters such as uniaxial compressive strength and modulus of elasticity can provide a good indication of predicting cutting disc wear. However, determining rocks' mineralogical and physical properties, such as texture, crystal size, and porosity, alongside their mechanical properties, is crucial in predicting rock wear.
6. Our findings advocate for the development of standardized linear cutting test methods that can be widely adopted to assess the performance of cutting tools under different geological settings. This would help in establishing more reliable benchmarks for TBM tool design and operation, ensuring that the tools are well-suited to the specific challenges of each tunneling project.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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بررسی تجربی اثرات خواص مکانیکی سنگ‌ها بر سایش ابزارهای برشی با استفاده از دستگاه جدید برش خطی در مقیاس کوچک

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کلمات کلیدی

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نیروهای برش

چکیده

امروزه با توجه به پیشرفت های تکنولوژیکی و افزایش تقاضا، انواع ماشین های حفاری تونل (TBM) به طور گسترده برای حفر تونل در خاک و سنگ استفاده می شود. روش حفاری مکانیکی در حفاری تونل و فضاهای زیرزمینی به دلیل ایمنی بالا، نرخ پیشروی بالا، نیاز به نیروی انسانی کم و قابلیت مکانیزاسیون بیشتر مورد استفاده قرار می‌گیرد. هزینه‌های سرمایه‌ای بالای حفاری مکانیکی، انجام آزمایش‌های آزمایشگاهی مانند آزمایش‌های برش خطی روی سنگ‌ها را قبل از انتخاب نوع دستگاه و تنظیم تیغه کله حفار ضروری می‌سازد. هدف اصلی این مطالعه، بررسی تأثیر خواص مکانیکی سنگ بر روی سایش ابزار برشی با استفاده از یک ماشین جدید برش خطی در مقیاس کوچک (LCM) است. برای دستیابی به این هدف، آزمایش‌های برش خطی آزمایشگاهی بر روی سنگ‌ها پس از ساخت دستگاه برش خطی در مقیاس کوچک انجام شد. برای ارزیابی قابلیت برش سنگ و تجزیه و تحلیل عملکرد دیسک کاترها، از ۵ نمونه سنگ در سه عمق نفوذ مختلف ۱، ۱/۵ و ۲ میلی متر استفاده شد. نتایج نشان داد که در همه سنگ‌ها، سایش دیسک‌های برشی با عمق نفوذ افزایش می‌یابد و بیشترین سایش در بازالت مشاهده شده است. علاوه بر این، آزمایش کشش برزیلی بیشترین همبستگی را با پارامترهای سایش دیسک برشی نشان داد. همچنین، مطالعات نشان داد که تعیین ویژگی‌های کانی‌شناسی و فیزیکی سنگ‌ها از جمله بافت، اندازه بلور و تخلخل، در کنار خواص مکانیکی آن‌ها، برای پیش‌بینی سایش سنگ بسیار مهم است.

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