



# Experimental Investigation on the Influence Factors on TBM Cutter Wear Based on Composite Abrasion Test

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## Abstract

Disc cutter wear is a crucial problem that influences the working efficiency and security of hard rock tunnel-boring machines (TBMs). When tunneling and rock breaking with TBM, the cutters at the forefront of the cutter head directly contact the tunnel face, where wear is serious due to a harsh working environment. In this study, the Cerchar abrasivity index (CAI) of various rock samples was obtained by using the ATA-IGG I rock abrasion servo system. Additionally, a series of small-size cutter wear experiments were carried out on an SP3-I composite abrasion test platform, and the fitting relationship between cutter wear and rock abrasion value was obtained. A cutter wear prediction method was established by measuring the cutter wear and rock CAI of the project built section and the rock CAI of the project unbuilt section. Based on the experimental results, the effects of different tunneling parameters (penetration speed, rolling speed) and tip width on cutter wear were analyzed. In the study of cutter wear, attention should be paid to the influence of load, vibration and temperature on the cutter wear removal mechanism. It is suggested that wide-tip and narrow-tip cutters should be arranged alternately on a TBM cutter head to give full play to the lateral rock crack ability developed by the wide-tip cutter and the radial rock crack ability developed by the narrow-tip cutter, so as to reduce wear on the cutter and improve the efficiency of TBM rock breaking. The results of this research provide a reference for optimization design and performance selection of a TBM cutter ring and cutter head.

**Keywords** TBM · Disc cutter · Composite abrasion test platform · Cerchar abrasivity index

## 1 Introduction

A Tunnel Boring Machine (TBM) is a multi-functional construction machine for cutting rock strata and excavating tunnels with tools. Due to its high mining efficiency, high safety and wide applicability, it is widely used in tunnel construction (Köppl et al. 2015; Mahdevari et al. 2014; Hassanpour 2018; Zhao et al. 2019). The disc cutter, as a tool that can be replaced with a cutting ring, is often mounted on the TBM cutter head in a radial distribution. During tunneling, the disc cutter rotates with the friction of the rock layer while the TBM cutter head revolves, thus producing a rolling cutting effect on the rock surface (Cho et al. 2013; Geng et al. 2016;

Gertsch et al. 2007; Ma et al. 2016). Therefore, the cutter ring is subjected to large contact stress. Undoubtedly, the complex cutting conditions of the tool ring can cause severe wear and tear, resulting in high consumption of the disc cutter and a high economic cost. A large amount of engineering data shows that the cost and time spent on maintenance and replacement of disc cutters accounts for almost one-third of project cost and construction time (Wang et al. 2017). Therefore, wear of the cutter ring has been a major concern in both academic and engineering fields.

Currently, studies on the wear of a disc cutter ring are mainly focused on the wear mechanism and prediction of cutter service life (Liu et al. 2017). Many researchers have studied the wear mechanism of the cutter ring. Tool wear is a process of material removal or cracking when it is in contact with other material (Farrokh and Kim 2018). Barzegari et al. (2015) found that there are three types of wear mechanisms: impact, adhesive wear and abrasive wear. Different wear mechanisms may lead to different wear processes, and in the case of TBM tunneling, tool wear may be a coupling effect of different wear mechanisms. Tool wear is affected

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by many factors, including rock properties, cutter type and material, and TBM cutter head design layout. These make the wear of the tool ring extremely complicated.

Some researchers have conducted research on the wear resistance of cutters and rock materials. Plinninger et al. (2003) analyzed the effects of experimental conditions and rock mass properties on the CAI index. Michalakopoulos et al. (2006) has shown more detailed information on the effects of experimental conditions and rock mass properties on the CAI index. Deliormanlı (2012) analyzed the Cerchar abrasivity index (CAI) and its relation to strength and abrasion test methods for marble stones. Al-Ameen and Waller (1994), West (1989), Yaralı et al. (2008), Er and Tuğrul (2016), and Capik and Yilmaz (2017) investigated the effect of rock strength and abrasive mineral content on the Cerchar abrasivity index (CAI) value. Macias et al. (2016) and Majeed and Bakar (2015) studied the influences of rock types on rock abrasivity. At the same time, some researchers have also studied the effect of tool ring characteristics on tool wear. For example, Lin et al. (2017) studied the specific matching characteristics between cutter ring hardness and rock. All of the aforementioned studies are helpful in understanding the wear characteristics of the cutter ring.

As for the wear prediction of cutter rings, many researchers have proposed different prediction models. Currently, the most commonly used are the CSM model (Rostami 1997) developed by the Colorado School of Mines and NTNU model (Bruland 1998; Macias 2016) developed by the Norwegian University of Science and Technology. Wijk (1992) proposed an equation for TBM cutter wear by using the rock strength index, the Cerchar abrasivity index (CAI), disc cutter geometry parameters, cutterhead thrust, and TBM boring distance. The hard rock TBM cutterhead energy equation is deduced by Wang et al. (2012, 2015), and a method for predicting disc cutter wear for a hard rock TBM cutterhead is advanced. Zhang et al. (2017) carried out an experimental study on wear behaviors of a TBM disc cutter ring under drying, water and seawater conditions. Zhang et al. (2018) also carried out experimental study on the wear of TBM disc cutter rings with different kinds of hardness. Ren et al. (2018) proposed a regressed equation to convert the consumed energy into the weight loss of a disc cutter and a new model to predict the lateral continuous wear of cutter rings.

When the cutter wears normally, multiple wear mechanisms participate at the same time (Espallargas et al. 2014). Cutter wear is mainly caused by the interaction between the cutter and the rock, and tool wear is composed of direct wear and secondary wear (Hassanpour et al. 2014; Petrica et al. 2013). Direct wear is the high-stress wear caused by the direct contact of the cutter with the rock, and it is the adhesive wear formed by the direct contact between two contact surface micro-peak bodies; secondary wear is the low-stress wear of the cutter caused by the rock ballast that

accumulates around the cutter, which is mainly caused by the sliding of loose particles. At present, the relatively mature and very representative Cerchar abrasivity experiment is mainly used to comprehensively measure the abrasiveness of rocks (Alber 2008; Ko et al. 2016). If the rock is too soft, there is no obvious wear after the steel needle moves. If the rock is too hard, no effective scratches can be formed. The CAI is also affected by the anisotropy of the rock sample. The Cerchar abrasivity experiment cannot directly predict cutter wear and cannot be effectively used to study primary and secondary wear of tools. Therefore, it is necessary to use a set of experimental platforms directly aimed at cutter wear on the basis of traditional rock abrasion parameters for cutter wear prediction and wear characteristics research.

In this paper, the ATA-IGG I rock abrasion servo system was used for an abrasion experiment on the rock samples. At the same time, a series of small-size cutter wear experiments were done using a SP3-I cutter composite abrasion test platform. The relationship between cutter wear and the rock Cerchar abrasivity index was established. The influence of cutter excavation parameters and tip width on cutter wear were compared and analyzed. A cutter wear prediction method was proposed by measuring the cutter wear and rock CAI of the project built section and the rock CAI of the project unbuilt section, providing a new ability to predict disc cutter wear state during TBM tunneling in real-time.

## 2 Experimental Program

### 2.1 Materials

Rock abrasiveness is one of the key factors affecting the degree of tool wear. Generally speaking, the abrasiveness of rocks is mainly related to the uniaxial compressive strength and mineral composition of rocks (Al-Ameen and Waller 1994; Petrica et al. 2013; Teymen 2020; Zhang et al. 2020). Through the identification of rock mineral composition, quartz content, mineral weighted hardness and equivalent quartz content of the rock can be accurately obtained, which provides reliable basic data for subsequent research. Sandy mudstone, sandstone, gneiss, basalt, diorite, marble, slightly weathered quartzite and slightly weathered granite were selected as the research objects in this study. The MTS815 rock mechanics testing machine was used to determine the uniaxial compressive strength of rock samples. The rock mineral X-ray diffractometer (XRD) was used to analyze the whole rock composition, and the mineral content in the rock was quantitatively determined. The crystal of each mineral has a specific X-ray diffraction pattern, and the characteristic intensity in the pattern is positively correlated with the mineral content in the sample. By measuring the characteristic intensity of a certain mineral in the sample, the mineral

content can be calculated. Rock samples mineral composition and uniaxial compressive strength are shown in Table 1.

### 2.2 Rock Cerchar Abrasivity Experiment

The abrasiveness of the rock plays an important role in the wear of a TBM cutter. The Cerchar abrasivity index (CAI) experiment is the most commonly used method to estimate rock abrasiveness due to its simple, fast test procedure and economic benefits. In the experiment, an alloy steel needle with a 90° cone angle is used to cross 10 mm on the rock surface at a speed of 10 mm/min under a load of 70 N. The average diameter of the needle tip loss (measured in 0.1 mm) is defined as the Cerchar abrasivity index.

In order to analyze the effect of rock abrasiveness on cutter wear, Cerchar abrasivity index experiments were carried out with an ATA-IGG I rock abrasion servo system of the State Key Laboratory of Shield Machine and Boring Technology (China Railway Tunnel Group Co., Ltd.). The main technical parameters of the experimental equipment are shown in Table 2.

In this experiment, eight types of rock samples were selected for rock abrasion experiments, and the CAI values of different rock samples were obtained. Three specimens were selected for each type of rock sample, and a total of 24 specimens were classified and numbered. Among them, #1–#3 are sandstone, #4–#6 are sandy mudstone, #7–#9 are gneiss, #10–#12 are basalt, #13–#15 are diorite, #16–#18 are marble, #19–#21 are slightly weathered quartzite, and #22–#24 are slightly weathered granite.

The rock sample was placed in the fixture, and the steel needle moved 10 mm horizontally at a displacement speed of 10 mm/min on the surface of the rock specimen. The wear diameters of the sliding steel needle under the high-definition digital microscope were measured under the axial direction (0), rotation 120° and rotation 240°, respectively. The abrasion values measured under the three angles were averaged arithmetically as a single experimental value. The experiment was repeated three times for each rock sample. Finally, the arithmetic average value of the test values of the three repeated experiments was the CAI value of the rock sample. In this experiment, the wear diameter of the steel needle was measured by 60-fold high-definition digital microscope, and the abrasion value of rock was obtained by formula (1) and formula (2) as follows.

$$d = L\alpha, \tag{1}$$

$$CAI = d/100, \tag{2}$$

where:  $d$  is the actual value of the wear diameter of the steel needle,  $\mu\text{m}$ ;  $L$  is the measured value of the wear diameter of the steel needle,  $\mu\text{m}$ ;  $\alpha$  is the calibration coefficient of the

**Table 1** Rock mineral composition and uniaxial compressive strength

Rock type	Mineral composition (%)							Equivalent quartz content (%)	Weighted hardness of rock minerals	Uniaxial compressive strength (MPa)
	Quartz (7/100)*	Potash feldspar (6/31)*	Plagioclase feldspar (6/31)*	Calcspar (3/3.6)*	Pyroxene (5.5/16)*	Magnesian limestone (3.7/3.8)	Clay mineral (1.5/0.21)*			
Sandy mudstone	37.9	1.8	9.8	9.2		38.3	3.0	41.9	4.2	35
Sandstone	64.8	8.9	15.7			6.5	4.1	72.4	6.1	40
Gneiss	36.3	29.6	25.2		3.8		5.1	53.9	6.0	100
Basalt	4.5		68.4		8.9	16.0	2.2	27.2	5.1	225
Diorite	32.2		43.6		20.3		3.9	49.0	6.0	156
Marble				20.2			7.5	3.5	3.3	78
Slightly-weathered quartzite	78.2			15.2			6.6	78.7	6.0	96
Slightly-weathered granite	36.8	22.8	32.8			5.7	1.9	54.0	6.0	177

Note: The value in ()\* is the Mohs hardness/Rosival grinding hardness of mineral (where Rosival grinding hardness is the relative value of quartz as 100)

**Table 2** The main technical parameters of ATA-IGG I rock abrasion servo system

Item	Parameter
Horizontal force effective measurement range (N)	0.4–200
Horizontal force measurement accuracy (%)	± 1
Vertical load of steel needle (N)	70
Steel needle dimensions	10 mm in diameter, 100 mm in length, 90° in cone angle
Steel needle material	40CrNiMo; HRC40–45
Axial grating displacement range (mm)	300
Horizontal grating displacement range (mm)	300
Displacement accuracy (%)	± 1
Displacement resolution	1/100,000
Horizontal velocity range (mm/min)	1–100
Microscopic magnification	60, 180, 540
Microscopic measurement accuracy (mm)	0.001

microscope; CAI is the rock abrasion value, 0.1 mm (Fig. 1; Table 3).

### 2.3 Cutter Wear Experiment

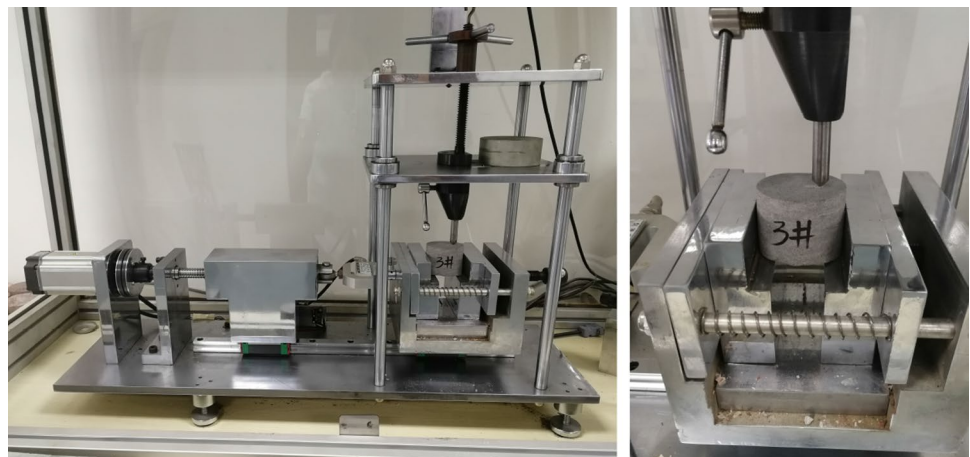
In order to analyze the various factors affecting cutter wear, a variety of rock samples were selected for the cutter wear experiment to study the effects of different penetration speeds, different rolling speeds and different tip widths on cutter wear.

The SP3-I cutter composite abrasion test platform is composed of a horizontal loading and controlling subsystem, vertical loading and controlling subsystem, rock sample and model cutter abrasion action mechanism, model cutter measurement subsystem, sub-system integration and experimental automatic control subsystem, as shown in Fig. 2. The horizontal motion actuator is driven by a hydraulic cylinder to control the speed or force of penetration into the rock; the vertical motion actuator is driven by a servo motor to


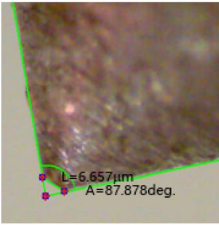
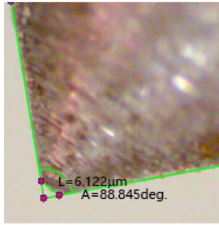
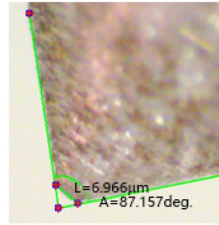

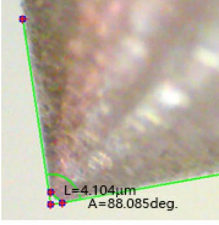
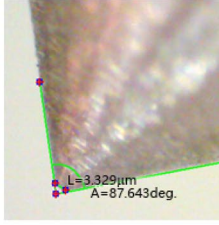
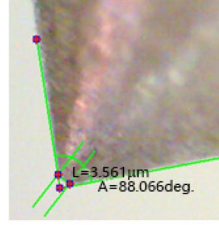
perform a reciprocating linear motion and control the speed of the rolling. The high-precision motion is realized by the EDC full digital servo controller and the sensor via a PID closed-loop control. Based on the principle of similarity, the test platform is designed at a ratio of 1:10. The design parameters are shown in Table 4.

The rock sample and model cutter abrasion mechanism consists of a rock sample, model cutter, rock sample fixture and cuttings box. The rock sample is processed by a two-way process of cutting and grinding to grow a rectangular parallelepiped with a width of  $(320 \pm 5 \text{ mm}) \times (70 \pm 2 \text{ mm}) \times (70 \pm 2 \text{ mm})$ , and the rock sample is fixed vertically by fixture (Fig. 3).

The material of the model cutter is the same as that of the construction site cutter ring, and it is consistent with the on-site cutter in the blank selection, machining process and heat surface treatment. The cutter material for the experiment is H13, and the composition is shown in Table 5. The density is  $7.9 \text{ g/cm}^3$ , the Rockwell hardness

**Fig. 1** #3 rock sample Cerchar abrasivity index experiment

**Table 3** Steel needle abrasion photographs (part)

Rock sample	Rock sample surface scratch	Steel needle abrasion photographs		
		0°	120°	240°
Sandstone				
				

HRC is between 57 and 59, and the impact toughness  $a_k$  is between 9 and 12 J/cm<sup>2</sup>. Based on the principle of simple processing and convenient installation, the model cutter adopts a similarly reduced cutter ring. The model cutter used in the experiment is shown in Fig. 4. According to the geometric similarity ratio of 1:10, the diameter of the cutter was reduced to 4.318 cm (1.7 in) and the tip shape is a flat tip of 1.9 mm and 2.5 mm. The mass measuring device is composed of an electronic micrometer, electronic percentile, vernier caliper and tape measure. These were used to measure the size and weight of cutters and rock samples before and after the experiment.

Before beginning the experiment, the model cutter is weighed, and then the fixed model cutter is installed. The model cutter reciprocates in a linear motion to cut the rock sample. When the cutter movement distance reaches the target value, the rock sample is separated from the cutter and unloaded. The model cutter is cleaned and weighed to calculate the mass loss. In the experiment looking at the influence of different tunneling parameters on cutter wear, in order to avoid the greater impact of contact between the hub and the rock face on the experimental results, the penetration depth in the experiment was controlled to be not more than 5 mm. When the penetration depth reaches 5 mm, the cutter rolls down to the next indentation. The cumulative rolling distance of a single cutter is 1 km, and continuous rolling of multiple rock samples of the same rock is carried out. The basic experimental parameters are set as shown in Table 6. The schematic diagram of cutter breaking rock is shown in Fig. 5.

In order to obtain the influence of different rock samples, different tunneling parameters and different tip widths on the cutter wear, the following experiments were done:

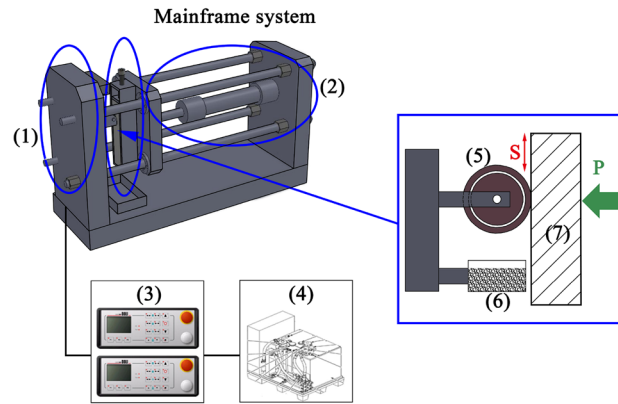
- (1) Effect of rock CAI on cutter wear
 

Without changing the basic parameters of the experiment, the relationship between cutter wear and the rock abrasion value was obtained by changing the type of rock sample.
- (2) Effect of different penetration speeds on cutter wear
 

The penetration speed of the cutter refers to the speed of the cutter penetrating the rock vertically. Based on the premise of keeping other parameters unchanged in the basic experimental parameters, only the penetration speed of the model cutter in the experiment was changed, and the relationship between the wear amount of the cutter and penetration speed was obtained. In order to ensure the comparability of the experiment, two kinds of rock (sandstone and sandy mudstone) were selected to carry out the comparative experiment at different penetration speeds. Six representative penetration speeds (0.12 mm/min, 0.16 mm/min, 0.2 mm/min, 0.24 mm/min, 0.28 mm/min and 0.32 mm/min) were selected for the cutter wear experiments at different penetration speeds. Considering the test accuracy of the test instrument, too high penetration speed are not used. When the penetration speed is too high, the rock sample is severely broken in a short time, and the data accuracy is difficult to guarantee.
- (3) Effect of different rolling speeds on cutter wear
 

Based on the premise of keeping other parameters unchanged in the basic experimental parameters, only the rolling speed of the model cutter in the experiment was changed, and the relationship between the wear amount of the cutter and rolling speed was obtained. In order to ensure comparability in the experiment, two types of rock (sandstone and sandy mudstone)

**Fig. 2** SP3-I cutter composite abrasion test platform



(a) Experimental device schematic ((1) Vertical loading and control subsystem (2) Horizontal loading and control subsystem (3) Measurement and control system (4) Power system (5) Model cutter (6) Rock chip box (7) Rock specimen)



(b) Experimental device physical diagram

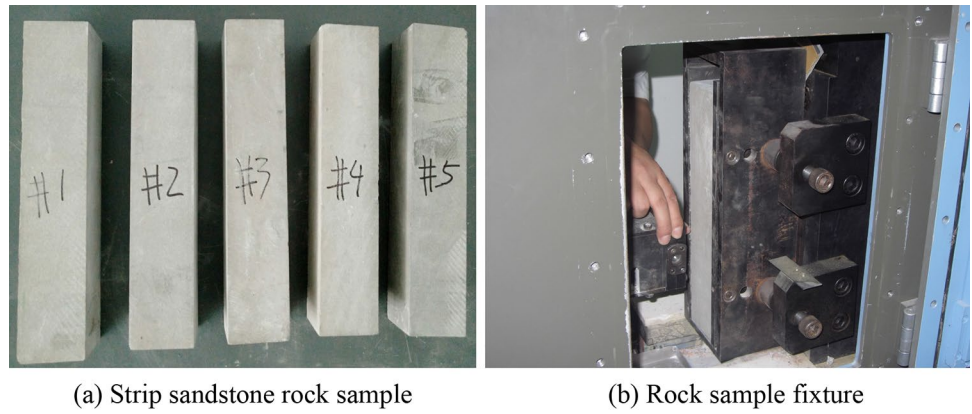
**Table 4** Key parameters of the cutter composite abrasion test platform

Key parameter	Model	Actual	Similarity ratio
Cutter diameter (mm)	43.18	431.8	1:10
Cutter trajectory	Straight line	Circular	–
Maximum angular velocity of cutter movement (r/s)	1.08	1.08	1:1
Maximum linear velocity of cutter movement (m/s)	0.1465	1.4653	1:10
Maximum rolling distance of cutter (cm)	29.3	293	1:10
Maximum horizontal load of cutter (kN)	2.5	250	1:100
Rock sample size (mm)	70 × 70 × 320	$R_{\max} = 14,000$	
Rock sample—cutter action direction	Horizontal	Horizontal	

were selected for the comparative experiment of different cutter rolling speeds. Seven representative rolling speeds (498 mm/min, 624 mm/min, 750 mm/min, 876 mm/min, 1002 mm/min, 1128 mm/min, 1248 mm/

min) were selected for the experiment of cutter wear under different rolling speeds.  
(4) Effect of different tip widths on cutter wear

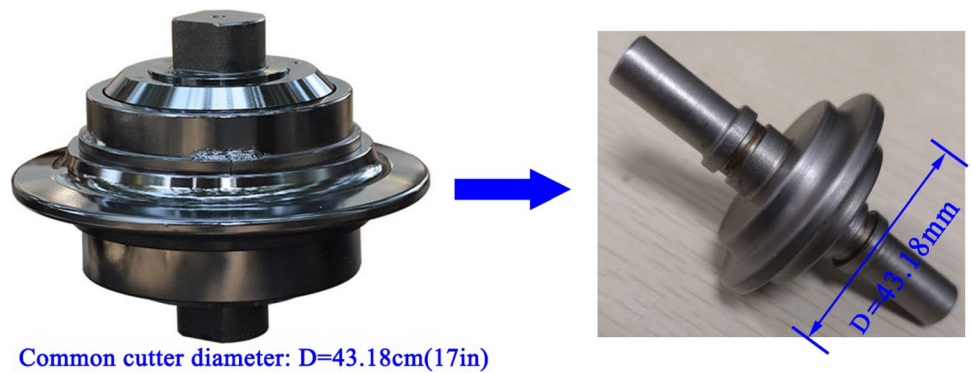
**Fig. 3** Strip rock sample and rock sample fixture



**Table 5** Chemical composition of cutter materials

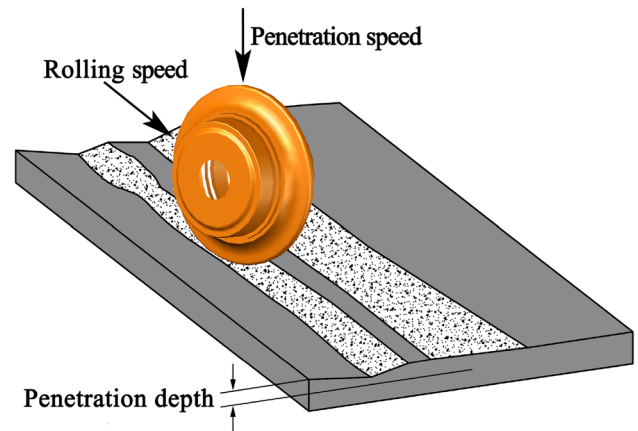
Composition	C	Si	Mn	Cr	Mo	V	P	S	Fe
Content (%)	0.32–0.45	0.80–1.20	0.20–0.50	4.75–5.50	1.10–1.75	0.80–1.20	≤0.03	≤0.03	Other

**Fig. 4** Model cutter for experiment



**Table 6** Basic experimental parameters settings

Item	Setting value
Rolling stroke	250 mm
Indentation spacing of rock sample surface	10 mm
Maximum rolling times per indentation	100
Rolling speed	1002 mm/min
Penetration speed	0.2 mm/min
Cumulative rolling distance of single cutter	1000 m
Cutter weighing	Weighed once every 50 m



**Fig. 5** Schematic diagram of cutter breaking rock

The relationship between amount of cutter wear and tip edge width was obtained by changing the tip width without changing the basic parameters of the experiment.

The working conditions of the cutter wear experiment are shown in Table 7.

**Table 7** Cutter wear experiment working conditions

Rock type	Penetration speed (mm/min)	Rolling speed (mm/min)	Tip width (mm)
Sandstone, sandy mudstone, gneiss, basalt, diorite, marble, slightly weathered quartzite, slightly weathered granite	0.2	1002	2.5
Sandstone, sandy mudstone	0.12, 0.16, 0.2, 0.24, 0.28, 0.32	1002	2.5
Sandstone, sandy mudstone	0.2	498, 624, 750, 876, 1002, 1128, 1248	2.5
Sandstone, sandy mudstone	0.2	1002	2.5, 1.9

### 3 Experimental Results and Analysis

#### 3.1 Effect of Rock CAI on Cutter Wear

Assuming that the material wear mechanism of the model cutter does not change compared with the actual cutter, the wear rate of the model cutter material can reflect the speed of actual cutter wear. By testing the cutter wear of different rocks, the relationship between cutter wear and rock abrasion value is established. In practical engineering,

according to the cutter wear record results of the built section of the project, the cutter wear amount of the unbuilt section of the project can be predicted. The results of the Cerchar abrasivity experiment and cutter wear experiment of each rock sample are shown in Tables 8 and 9, respectively.

Table 9 shows that the uniaxial compressive strength of marble is less than that of gneiss, but its abrasion value is higher than that of gneiss and the CAI value of the former is 1.5 times that of the latter. The kilometer wear of the cutter in marble is also higher than that in gneiss, and the

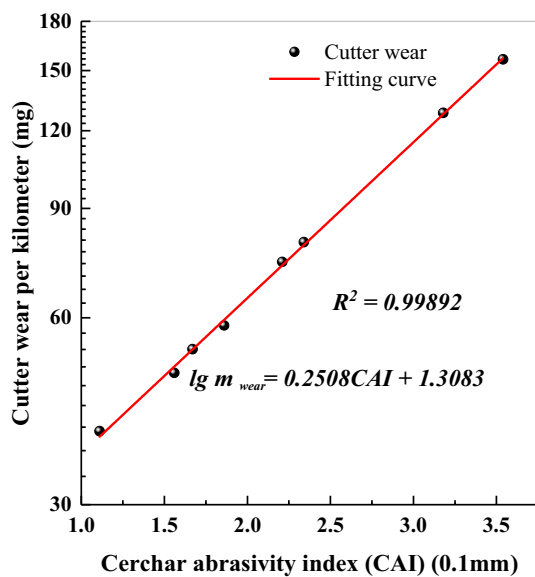
**Table 8** Rock Cerchar abrasivity experiment results

Rock sample	Number	Measured value			Mean CAI value (standard deviation)
Sandstone	#1	2.246	2.211	2.141	2.21 (0.126)
	#2	2.152	2.019	2.229	
	#3	2.090	2.404	2.380	
Sandy mudstone	#4	1.296	1.126	1.184	1.11 (0.115)
	#5	1.102	1.005	1.195	
	#6	0.953	1.143	0.964	
Gneiss	#7	1.258	1.343	1.386	1.56 (0.242)
	#8	1.696	1.550	1.323	
	#9	1.752	1.899	1.833	
Basalt	#10	1.623	1.666	1.667	1.67 (0.120)
	#11	1.584	1.691	1.441	
	#12	1.819	1.697	1.842	
Diorite	#13	1.864	2.014	1.996	1.86 (0.126)
	#14	1.888	1.790	1.878	
	#15	1.653	1.697	1.960	
Marble	#16	1.994	1.855	2.589	2.34 (0.258)
	#17	2.608	2.472	2.366	
	#18	2.450	2.445	2.281	
Slightly weathered quartzite	#19	2.891	3.157	3.414	3.18 (0.323)
	#20	2.755	3.286	2.905	
	#21	3.687	2.984	3.541	
Slightly weathered granite	#22	3.421	3.658	3.421	3.54 (0.221)
	#23	3.674	3.591	3.991	
	#24	3.520	3.312	3.272	



**Table 9** Wear experiment results of different rock

Rock type	CAI	Uniaxial compressive strength (MPa)	Cutter wear per kilometer (mg)
Sandy mudstone	1.11	35	39.4
Sandstone	2.21	40	73.8
Gneiss	1.56	100	48.9
Basalt	1.67	225	53.4
Diorite	1.86	156	58.3
Marble	2.34	78	79.4
Slightly-weathered quartzite	3.18	96	128.2
Slightly-weathered granite	3.54	177	156.4



**Fig. 6** Relationship curve of the between cutter wear per kilometer and rock CAI value

wear of the former is almost 1.6 times that of the latter. The uniaxial compressive strength of slightly weathered quartzite is equivalent to that of gneiss, but its abrasion value is 2.0 times that of gneiss, and the kilometer wear of the cutter is 2.6 times that of the latter. The uniaxial compressive strength of basalt is much greater than the uniaxial compressive strength of gneiss, but its abrasion value is almost the same, and there is no significant difference in cutter wear. Both slightly weathered quartzite and slightly weathered quartzite have high CAI values and are highly abrasive to the cutter. Therefore, it can be speculated that the cutter wear has a certain relationship with the uniaxial compressive strength of rock, but the main influencing factor is the rock abrasivity index, and it should have a certain correlation with the rock abrasivity

index. The relationship between the cutter wear and the rock CAI value is shown in Fig. 6.

By fitting the above experimental results, the relationship between the cutter wear per kilometer and rock CAI value is obtained:

$$lg m_{wear} = 0.2508CAI + 1.3083. \tag{3}$$

Then the prediction formula of cutter wear is as follows:

$$\frac{lg m_{wear1}}{lg m_{wear2}} = \alpha \frac{CAI_1 + 5.2165}{CAI_2 + 5.2165}, \tag{4}$$

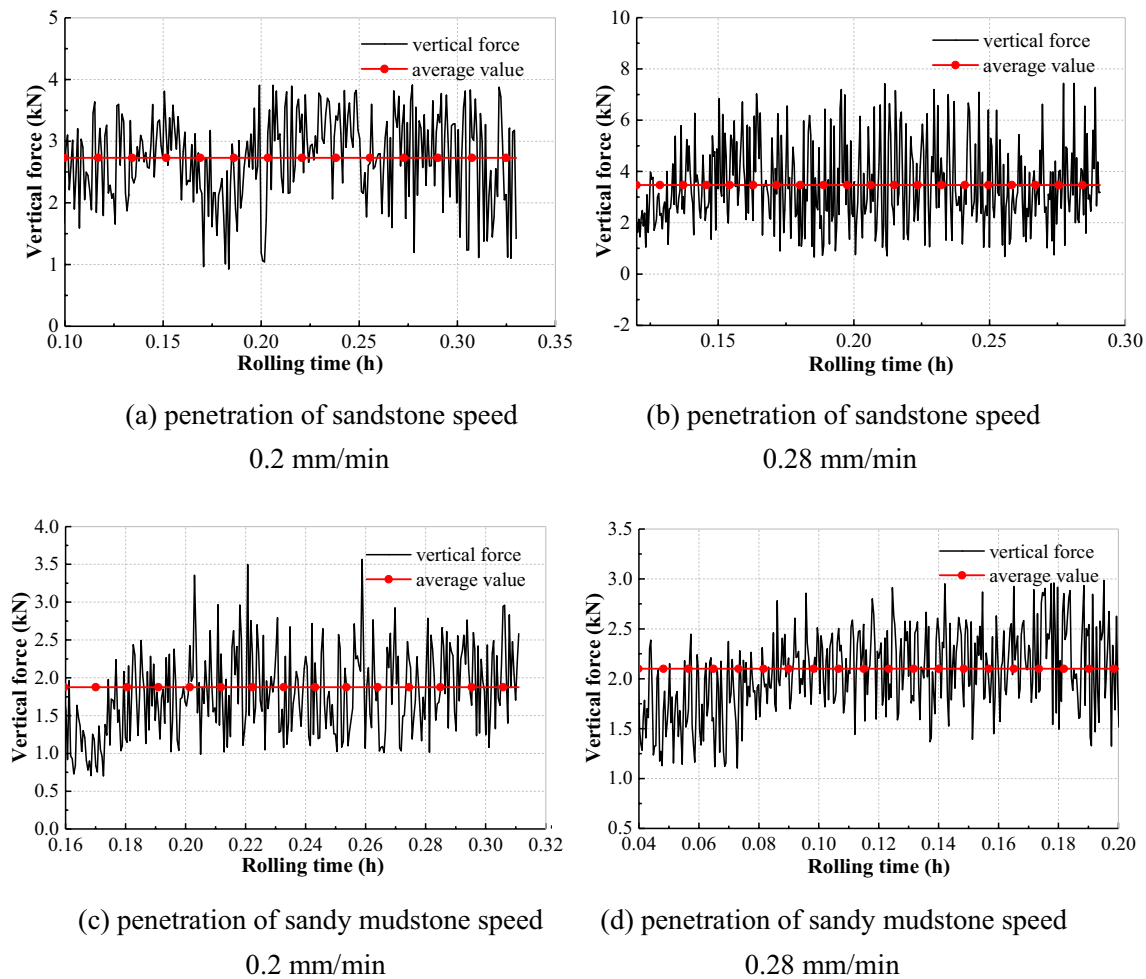
where:  $m_{wear1}$  is the cutter wear of the project built section;  $CAI_1$  is the rock abrasivity index of the project built section;  $m_{wear2}$  is the cutter wear of the project unbuilt section;  $CAI_2$  is the rock abrasivity index of the project unbuilt section; and  $\alpha$  is the correction factor.

By measuring cutter wear and the rock abrasivity index of the built section of the project and the rock abrasivity index of the unbuilt section of the project, the cutter wear of the unbuilt section of the project can be predicted by formula (4).

### 3.2 Effect of Penetration Speed on Cutter Wear

Figure 7 shows the cutter vertical force fluctuation curves of sandstone and sandy mudstone at penetration speeds of 0.2 mm/min and 0.28 mm/min, respectively. The figure shows that the force on the cutter is constantly oscillating during the whole cutting process. The high-frequency oscillation of cutter force reflects the instability of the rock cutting process.

Considering that the vertical force of the cutter is constantly changing, the analysis in this paper only studies the average value of the vertical force during the entire rolling process. The vertical force data collected by the system during the entire cutter rolling process are averaged as the vertical force average value. The average value of vertical force and the cutter wear per kilometer of sandstone and sandy mudstone under different penetration speeds are analyzed, as shown in Table 10 and Fig. 8. Intuitively from the figure, the average value of the vertical force and cutter wear increases with an increase in penetration speed, which is mutually verified with the damage degree of the rock sample. That is, with an increase of penetration, the disturbance degree of surrounding rock increases. Since damage to the rock is mainly due to the squeezing action of the disc cutter tip on the rock, the increase in penetration speed means that the speed of the cutter cutting into the rock increases. The contact area between the disc cutter and the rock, the volume of broken rock, and the tightness of the compaction core under the cutter tip will all increase.



**Fig. 7** Vertical force fluctuation curve of cutter under different penetration speeds

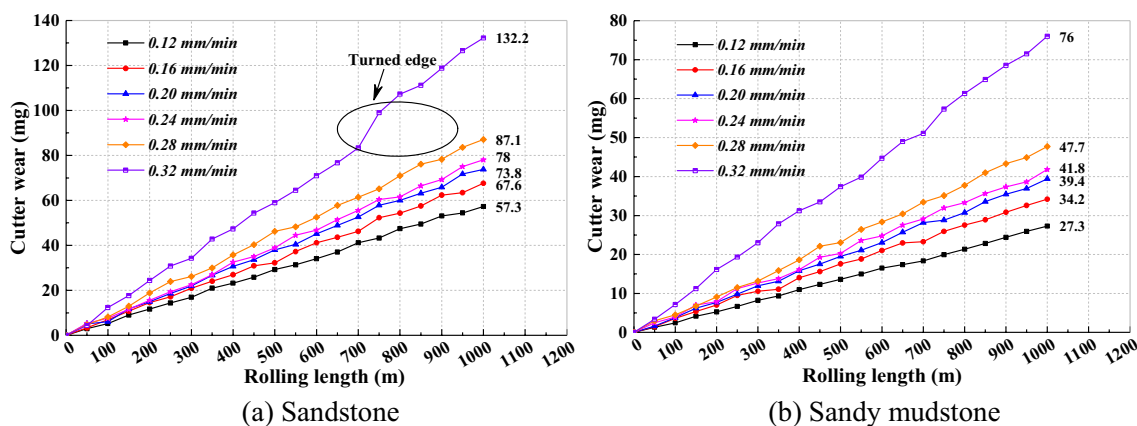
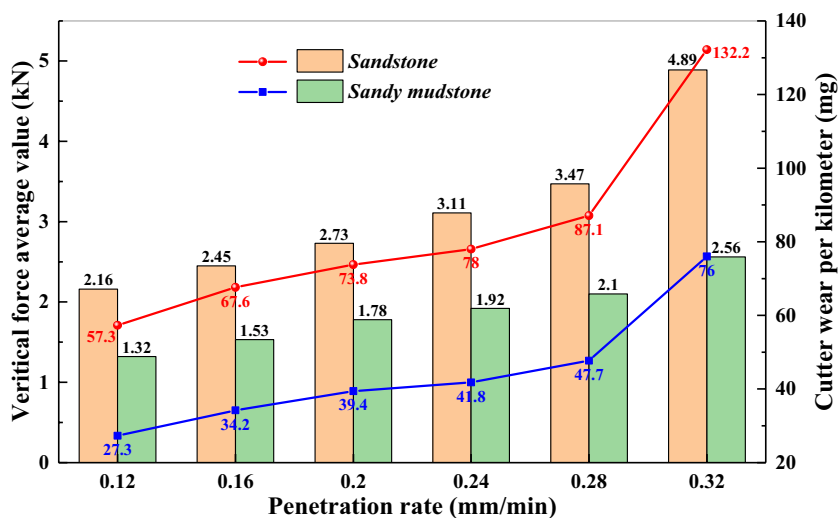
**Table 10** Average value of cutter vertical force and wear per kilometer at different penetration speeds

Penetration speed (mm/min)	Rolling speed (mm/min)	Tip width (mm)	Model cutter vertical force mean (kN)		Model cutter wear per kilometer (mm)	
			Sandstone	Sandy mudstone	Sandstone	Sandy mudstone
0.12	1002	2.5	2.16	1.32	57.3	27.3
0.16			2.45	1.53	67.6	34.2
0.2			2.73	1.78	73.8	39.4
0.24			3.11	1.92	78.0	41.8
0.28			3.47	2.1	87.1	47.7
0.32			4.89	2.56	132.2	76.0

However, it should also be noted that with an increase of penetration speed, the cutter wear rate shows a difference. When the penetration speed is at a low level, the mass wear rate of the cutter decreases with an increase of the penetration speed. When the penetration speed reaches a certain value, the mass wear rate of the cutter increases sharply with an increase of the penetration speed. This is

mainly due to the increase of the cutter force at a large penetration speed, where the load vibration frequency and the temperature of the cutter also increase. The cutter wear mechanism changes from micro-cutting to a brittle fracture removal mechanism, and the change of wear mechanism leads to a sharp increase in cutter wear.

**Fig. 8** Vertical force mean and wear per kilometer of cutter under different penetration speeds



**Fig. 9** Relationship curve between cutter wear and rolling distance under different penetration speeds

Figure 9 shows the cutter wear curve with rolling distance at different penetration speeds. Through comparative analysis, the following conclusions can be drawn:

- (1) The wear amount of the cutter is basically linear with rolling distance, and as the penetration speed increases, the cutter wear rate also increases.
- (2) Cutter wear in sandstone is significantly greater than in sandy mudstone, which verifies the correlation between the cutter wear amount and the rock abrasion value.
- (3) When the penetration speed is low, the cutter wear amount is almost linear with the penetration speed. When the penetration speed increases to 0.32 mm/min, a turning point appears in the cutter wear curve. The main reason is that the increase in penetration speed leads to a larger load on the cutter, which in turn increases the plastic deformation of the cutter material, causing the edge of the tip to curl. Material brittleness removal is aggravated after edge curling, resulting in a

large amount of material peeling off and an increase in the wear amount. Therefore, it is recommended that in a specific engineering practice, the normal wear zone of the cutter should be found by adjusting the penetration speed in the TBM trial excavation section. In the later TBM excavation, the penetration speed should be controlled within the curve gentle zone as far as possible, that is, to ensure efficient rock breaking of TBM without overly serious cutter wear.

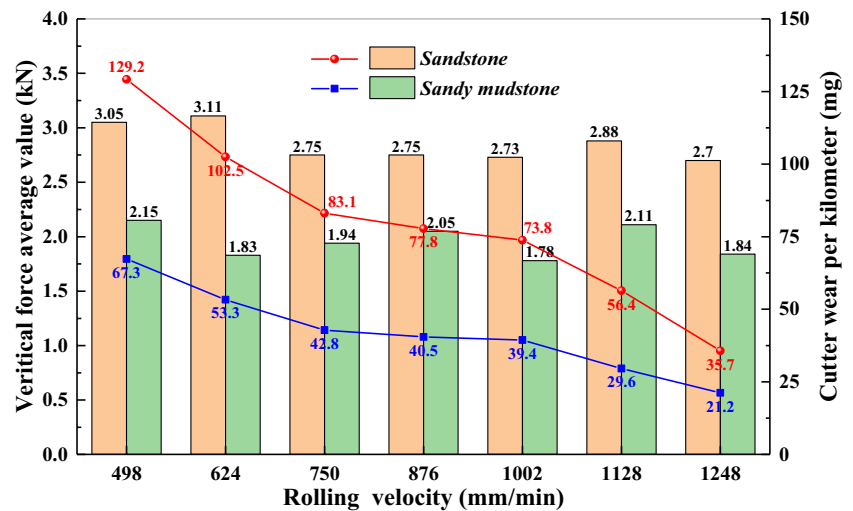
### 3.3 Effect of Rolling Speed on Cutter Wear

The average value of vertical force and the cutter wear per kilometer of sandstone and sandy mudstone under different penetration speeds are shown in Table 11 and Fig. 10.

Figure 10 shows that the fluctuation range and average value of the cutter vertical force under different rolling speeds are almost the same, indicating that the cutter vertical force has little correlation with rolling speed. The essence

**Table 11** Average value of cutter vertical force and wear per kilometer at different rolling speeds

Penetration speed (mm/min)	Rolling speed (mm/min)	Tip width (mm)	Model cutter vertical force mean (kN)		Model cutter wear per kilometer (mm)	
			Sandstone	Sandy mudstone	Sandstone	Sandy mudstone
0.2	498	2.5	3.05	2.15	129.2	67.3
	624		3.11	1.83	102.5	53.3
	750		2.75	1.94	83.1	42.8
	876		2.75	2.05	77.8	40.5
	1002		2.73	1.78	73.8	39.4
	1128		2.88	2.11	56.4	29.6
	1248		2.70	1.84	35.7	21.2

**Fig. 10** Vertical force mean and wear per kilometer of cutter under different rolling speeds

of the rock crushing process is the formation, propagation and fracture process of rock cracks under the contact effect of a cutter tip. In the current range of cutter cutting speeds, the propagation of rock cracks is little affected by the cutting speed, which also shows that the cutting speed of a cutter has little effect on the cutter force.

From the point of view of the cutter wear amount per kilometer, with other experimental conditions unchanged, with an increase of rolling speed for the model cutters, the cutter wear also gradually decreases. It is worth noting that the relationship between them is not a strictly linear proportional relationship. As the rolling speed increases, the cutter wear decreases almost linearly at first, and then a gentle zone is formed in a certain area. With a further increase of rolling speed, the wear rate will decrease sharply. The reason may be that under a high rolling speed, the rock sample is seriously damaged, and the large rock blocks fall off from the rock sample, resulting in inadequate contact between cutter and rock sample and reduction of wear. It is suggested that in a specific engineering practice, in the TBM trial excavation section, the gentle area of cutter wear can be found by adjusting the rotational speed of the cutter head. In the

later excavation, the cutter wear can be controlled within the gentle area as far as possible, which ensures efficient rock breaking of TBM without causing too much disturbance to the surrounding rock.

The relationship curve between cutter wear and rolling distance under different rolling speeds is shown in Fig. 11. The figure shows that cutter wear basically increases linearly with cutter rolling distance. Overall, for cutters with two tip widths, the linear relationship between cutter wear and rolling distance is better at low and medium rolling speeds, and slightly worse at high rolling speeds. The reason is that the cutter and the rock interact more intensely at high rolling speeds, the interaction time is shorter, the difference of rolling distance per 100 m is larger, and the fluctuation of the curve is stronger macroscopically.

### 3.4 Effect of Tip Width on Cutter Wear

Figure 12 shows the relationship between the cutter wear amount and the rolling distance under different tip widths. Analysis shows the following:

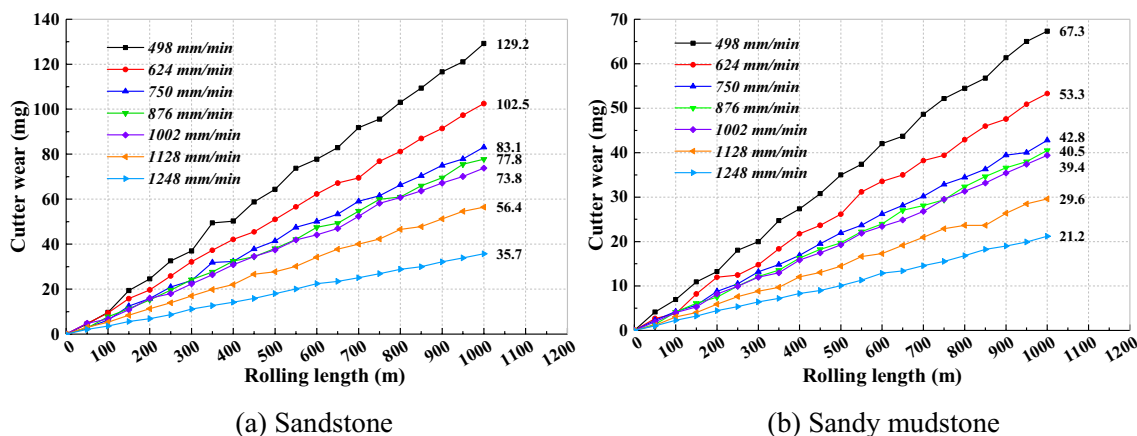


Fig. 11 Relationship curve between cutter wear and rolling distance under different rolling speeds

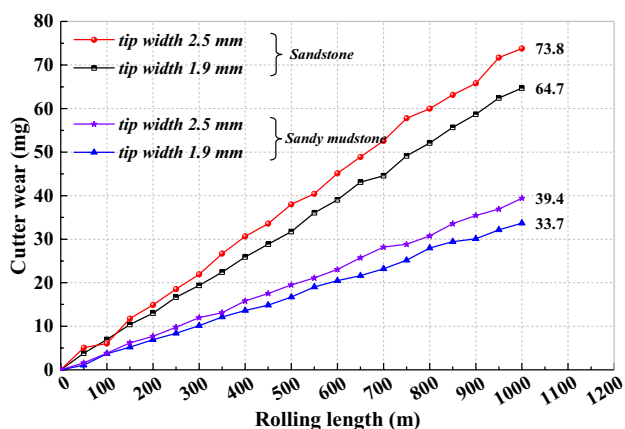


Fig. 12 Relationship curve between cutter wear and rolling distance under different tip widths

- (1) The mean vertical force and wear of the wide-tip cutter are greater than those of the corresponding narrow-tip cutter.
- (2) Under different tip widths, the cutter wear in sandstone is greater than that in sandy mudstone, which proves once again that rock abrasion is the first index affecting the cutter wear.
- (3) Cutter wear is positively correlated with tip width. The larger the contact area is, the more serious the wear. However, the tip width has a compensation effect on the radial wear of the cutter, that is, the radial wear of the wide-tip cutter is smaller under the same tunneling distance.

From the experimental load data, the load on the cutter does not decrease significantly due to a narrowing of the tip.

According to the fracture degree and slag morphology of rock samples after rock breaking by a cutter, the slag produced by a narrow-tip cutter is mostly powdered and less

massive. The reason is that the local pressure between the narrow-tip cutter and the rock increases, and the rock is easy develops deep radial cracks. The lateral cracks cannot effectively expand, and it is difficult to produce a large volume of broken blocks with lateral development.

In the optimization design of the TBM cutter head cutter, it is suggested that wide-tip and narrow-tip cutters should be arranged alternately to give full play to the lateral rock crack ability developed by the wide-tip cutter and the radial rock crack ability developed by the narrow-tip cutter, so as to reduce the wear of the cutter and improve the efficiency of TBM rock breaking.

### 4 Conclusions

In this paper, the ATA-IGG I rock abrasion servo system was used to conduct an abrasion experiment on rock samples. Concurrently, a series of small-size cutter wear experiments were carried out by using a SP3-I cutter composite abrasion test platform. The main conclusions are as follows:

- (1) The main factor affecting cutter wear is rock abrasion value. The fitting relationship between cutter wear and rock abrasion value was obtained. A cutter wear prediction method was established by measuring the cutter wear and rock CAI of the project built section and the rock CAI of the project unbuilt section.
- (2) When the penetration speed is at a low level, the mass wear rate of the cutter decreases with an increase of the penetration speed. When the penetration speed reaches a certain value, the mass wear rate of the cutter increases sharply with the increase of the penetration speed. This is mainly due to the increase of the cutter force at a large penetration speed, as the load vibration frequency and the temperature of the cutter also

increase. The cutter wear mechanism changes from a micro-cutting to brittle fracture removal mechanism, and the change in wear mechanism leads to a sharp increase in cutter wear.

- (3) The vertical force of a cutter has little correlation with rolling speed. At a high rolling speed, the rock sample is seriously damaged, and large pieces of rock slag fall off from the rock sample. The cutter does not come fully into contact with the rock sample, resulting in a reduction of cutter wear.
- (4) In the optimization design of the TBM cutter head cutter, it is suggested that the wide-tip and narrow-tip cutters should be arranged alternately to give full play to the lateral rock crack ability developed by the wide-tip cutter and the radial rock crack ability developed by the narrow-tip cutter, so as to reduce the wear of the cutter and improve the efficiency of TBM rock breaking.

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