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Relationship between Rock Abrasivity and Tensile Strength

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Abstract: We discussed the relationship between rock abrasivity and tensile strength so as to provide clues for the choice of cutting head of tunnel boring machine. A total of 24 samples belonging to four lithologies were tested for abrasivity and uniaxial tensile strength. Correlation analysis indicated that rock abrasivity is not a mathematical function of tensile strength; rather, the two have a positive correlation in a qualitative sense. Two influence factors of rock abrasivity are contents of hard minerals (typically the quartz) and the mode and strength of mineral bonding (crystallization and cementation). We found that rock abrasivity is the result of combined action of several factors. In tunnel construction, the choice of cutting head of TBM should be based on consideration of the effect of several factors on rock abrasivity.

***Keywords:** Rock abrasivity, Tensile strength, Mineral composition, Tunnel Boring Machine (TBM)*

1. Introduction

Rock abrasivity is an important parameter in the choice of cutting head of tunnel boring machine (TBM). The abrasion of cutting head, the wear part of TBM, has a direct bearing on the tunneling efficiency and economic benefits of TBM. Rock abrasivity is closely connected to the physical properties and other inherent characteristics of rocks, such as mineral content and texture.

Rock is the aggregate of several kinds of minerals. Due to the development of TBM tunneling technology and the increased tunneling depth and the complexity of tunneling across different strata, rock abrasivity has become a hot topic [1-15]. Many models have been proposed to describe the relationship between rock abrasivity and tunneling performance [16]. Cerchar abrasion test is the most commonly used test method, and Cerchar abrasion index (CAI) has been extensively studied. Suana and Peters investigated the effect of equivalent quartz content (EQC) and particle size on CAI [17]. Al-Ameen and Wallner focused on the relationship between rock strength and CAI [18], suggesting that rock strength had the greatest impact on CAI. Plinninger made an investigation on the impact of test conditions and physico-mechanical properties of rocks on CAI [19].

Moradizadeh et al. predicted CAI based on the mineral composition of sandstone [20]. Rostami et al. analyzed the influence factors of CAI [21]. Tumac argued that physico-mechanical properties of natural rocks had a significant impact on CAI [22]. Though several influence factors of CAI are mentioned in the above studies, mechanical strength and EQC of rocks have the strongest correlation with CAI. To further elucidate the connections between mechanical strength of rocks and CAI, Wang, Luo and Wang et al. analyzed the correlations between rock abrasivity and mechanical strength and mineral composition of rocks. They found that rock abrasivity is exponentially related to the mechanical strength.

Deliormanlı and Liu et al. derived the linear relationship between rock abrasivity and mechanical strength [23-25]. Kahraman, by carrying out similar experiments [26], found that rock abrasivity is logarithmically related to the mechanical strength. Obviously, the relationship between CAI and mechanical strength and mineral composition of the rocks thus derived varies from one study to another, and there is also a difference in the fitted equations.

Given such large disparity in the experimental findings, they can hardly benefit the engineering applications. We performed uniaxial tensile test on sandstone samples in an attempt to find out any precise quantitative relationship between uniaxial tensile strength and CAI.

2. Characteristics and composition of rock samples

2.1. Sample description

The rock cores used in the test were collected by drilling. From fine to coarse, the samples were divided by particle size into four types, namely, sandstone, silty mudstone, siltstone and fine sandstone. The rocks were formed in Early Miocene, all being discs with uniform diameter of 5cm and height of 2.5cm (Brazilian discs, Fig. 1).

There were 5 mudstone samples (marked by M) in dark red color; 5 silty mudstone samples (marked by SM) in dark red color; 3 siltstone samples (marked by S0) in red color; 12 fine sandstone samples (marked by S and SS) in grayish white color (Table 1).

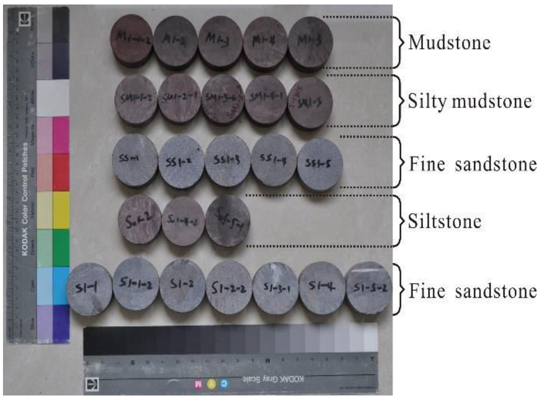

Figure 1: *Photos before the rock abrasion test (24 effective data except the sample S1-2-2)*

Table 1: *Sample list of rock abrasion test*

Fine sandstone “S/SS”		**Siltstone “S0”**	**Silty mudstone “SM”**	**Mudstone “M”**
S1-1	SS1-1	S01-2	SM1-1-2	M1-1-2
S1-1-2	SS1-2	S01-4-2	SM1-2-1	M1-2
S1-2	SS1-3	S01-5-1	SM1-3-2	M1-3
S1-3-1	SS1-4		SM1-4-1	M1-4
S1-4	SS1-5		SM1-5	M1-5
S1-5-2				

2.2. Mineral composition analysis by X-ray diffraction (XRD)

One sample was selected for XRD for each of the four lithologies using D/MAX-2400 XRD analyzer. The test results are shown in Table 2.

It can be seen from the table that quartz and calcite are the major minerals of the samples, both accounting for 85-90% of total mass. And the four samples slightly differed in mineral types, there was only a small difference in mineral contents.

Table 2: *Results of mineral composition test by XRD method*

Sample No.	**Type and content of minerals / %**									**Total content/ %**
	Non-clay minerals							**Clay minerals**		
	Quartz	**Calcite**	**Albite**	**Dolomite**	**Muscovite**	**Hematite**	**Plagioclase**	**Kaolinite**	**Chlorite**	
M1-3	63.56	23.54	1.67	3.59				3.49	4.16	100.01
SM1-1-2	61.09	23.64			6.26	1.87	2.17	2.02	2.96	100.01
SS1-1	72.13	16.58	4.26	3.59	2.08			1.36		100
S1-3-1	66.73	24.31	2.81	3.69	1.5			0.95		99.99

3. Brief description of the test

3.1 Brief description of the rock abrasion test

The abrasion test made use of the Cerchar abrasion method developed in 1970 by Cerchar Institute. The test equipment was able to measure and compare the rock abrasivity of different samples conveniently and rapidly. Now CAI is considered to be a standard parameter for the abrasion classification of hard rocks [27].

Rock abrasivitiy was measured by the ATA-IGG I type rock abrasion servo tester developed by Institute of Geology and Geophysics, CAS (Fig. 2). The technical parameters of the tester are shown in Table 3.

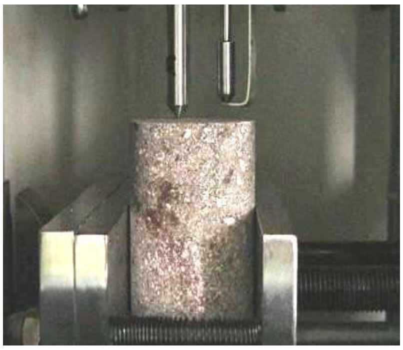

Fig 2: *ATA-IGG I type rock abrasion servo tester*

Table 3: *Specific technical parameters of the ATA-IGG I type rock abrasion servo tester*

Technical parameters	**ATA-IGG Ⅰ type rock abrasion servo tester**
Measurement range of horizontal force	0.4-200N
Measurement precision of horizontal force	±1%
Vertical load of steel stylus	70N
Specification of steel stylus	Diameter 10mm, length 100mm, cone angle 90°
Material of steel stylus	40CrNiMo; HRC40-45
Displacement precision	±1%
Displacement resolution	1/100000
Magnification times	×60, ×180, ×540
Measurement precision of microscope	0.0001mm

3.2 Procedures of rock abrasion test

The test procedures recommended by International Society for Rock Mechanics (ISRM) were used [28]:

a. Disc-shaped samples with fresh and smooth surface were used;

b. Before test, the tip of the steel stylus was examined under high-power light microscope (Aigo) to check whether the cone angle was 90° (i.e., not worn);

c. The rock samples were fixed with the fresh surface facing upward. The steel stylus was installed so that it was in close contact with the tested surface. The load was imposed and the cabin door was closed.

d. Parameters were configured on the computer. Click on the button “Start” and the steel stylus would move by 1cm over the rock surface under the control of the tester.

e. After the abrasion test, the steel stylus was dismounted and observed under the microscope. The length of wearing was recorded and accurate to 0.0001mm.

f. The tip of the steel stylus was scratched over the smoother surface of the rock in orthogonal direction. And the average value was taken as the CAI.

3.3 Brief description of the uniaxial tensile test

As an important mechanical parameter, uniaxial tensile strength is the maximum stress that the rock can withstand under uniaxial tension.

The test was carried out on an 800kN press machine by the splitting test. The disc-shaped samples with diameter of 5cm and height of 2.5cm were transversely placed on the load bearing plate of the press machine. One strip was attached to the upper and lower sides of the specimen, respectively, and the load was imposed at the rate of 0.3-0.5MPa/s until failure (Fig. 3). This method is also known as Brazilian disc method. The test conformed to Standard for Tests Method of Engineering Rock Masses (GB/T 50266-99).

Fig 3: *Comparison photos of sample SS1-2 before and after tensile test*

4. Test Results

The rock abrasivity and uniaxial tensile strength of the samples are shown in Table 4. Fine sandstone has higher abrasivity, while silty mudstone has higher tensile strength; the abrasivity and tensile strength of the mudstone and siltstone are low. This is because the hard minerals (typically quartz) in the fine sandstone have larger particles and therefore higher abrasivity. Silty mudstone has better particle size gradation and better skeleton. The more intense cementation in silty mudstone leads to higher mechanical strength (including uniaxial tensile strength). Due to higher content of mud components and clay, mudstone and siltstone have poor particle size gradation and hence lower mechanical strength and abrasivity.

Table 4: *Results of rock abrasivity and uniaxial tensile strength test*

Lithology	Sample No.	Abrasivity / 0.1mm	Uniaxial tensile strength / Mpa
Fine sandstone “S”	S1-1	3.144	6.416
	S1-1-2	3.128	7.979
	S1-2	3.165	8.977
	S1-3-1	2.964	6.857
	S1-4	2.919	5.897
	S1-5-2	2.997	6.359
	SS1-1	1.916	3.840
	SS1-2	3.029	7.572
	SS1-3	2.773	5.796
	SS1-4	2.114	3.849
	SS1-5	1.214	5.238
Siltstone “SS/S0”	S01-2	1.258	5.137
	S01-4-2	0.851	4.627
	S01-5-1	1.782	2.846
Silty mudstone “SM”	SM1-1-2	1.705	10.348
	SM1-2-1	1.595	9.349
	SM1-3-2	1.314	9.143
	SM1-4-1	1.135	8.204
	SM1-5	1.077	7.104
Mudstone “M”	M1-1-2	1.429	2.286
	M1-2	1.839	3.801
	M1-3	1.000	1.921
	M1-4	1.157	4.311
	M1-5	0.965	3.434

5. Relationship between rock abrasivity and uniaxial tensile strength

Correlation analysis was carried out based on the measurements of rock abrasivity and uniaxial tensile strength (Fig. 4). Considering the effect of lithology, the curves were fitted separately for each lithology and the correlation coefficients were calculated. The fitted results are shown in the figure below.

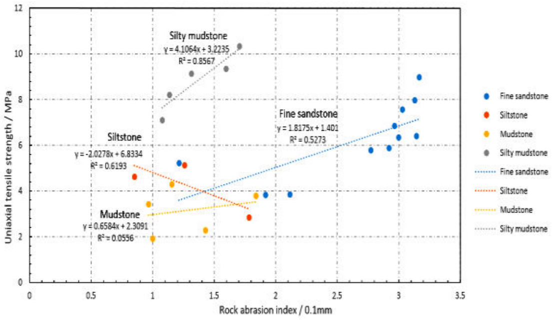

Figure 4: *Correlation between the rock abrasivity and uniaxial tensile strength*

The data shows high degree of discreteness, and we cannot identify an explicit correlation between uniaxial tensile strength and rock abrasivity. Only after classification by lithology can we observe a positive correlation between the two and the correlation coefficients vary greatly. Correlation coefficient R^2 is the highest for silty mudstone (0.857), and the lowest for mudstone (0.056). The correlation coefficients are positive for only 3 lithologies, and it is negative for siltstone. Since there are only 3 sets of values available for the siltstone, the results are not representative in the statistical sense.

Our results are compared with the results by other researchers (Table 5). The correlation coefficients vary from one study to another, but most researches indicate a positive correlation.

Therefore, this study shows that the rock abrasivity is positively correlated with tensile strength in a qualitative sense, but we can hardly derive a mathematical relationship between the two. Generally the higher the mechanical strength of the rocks, the higher the rock abrasivity and the more severe the wearing of the TBM cutting head will be.

Table 5: *Comparison of the relationship between rock abrasivity and mechanical strength*

Lithology	**Mathematical expression**	**Source**	**Type of correlation**	**Correlation coefficient R2**
Tuff	$CAI=0.148\sigma_t+2.742$	Liu, 2014	Linear	0.59
Tuff	$CAI=0.170\sigma_{st}+2.915$	Liu,2014	Linear	0.67
Three major types of rock	$CAI=0.015\times\sigma_c^{0.788}\times EQC^{0.377}$	Rostami,2014	Power	0.90
Marble	$\sigma_c=54.47CAI+18.26$	Deliormanlı A H,2012	Linear	0.81
Three major types of rock	$\sigma_t=5\exp^{0.653CAI}$	Wang, 2010	Exponential	0.84
Three major types of rock	$\sigma_t=3.015\exp^{0.279CAI}$	Wang, 2009	Exponential	0.87
Artificial sand	$LA=25268/\sigma_c^{1.442}$	Kılıç A,2007	Power	0.95
Three major types of rock	$LA=-24.12\ln\sigma_c+143.78$	S. Kahraman.,2007	Logarithmic	0.63
Igneous rock	$LA=-26.23\ln\sigma_c+150.81$	S. Kahraman.,2007	Logarithmic	0.50
Three major types of rock	$\sigma_t=3.07\exp^{0.277CAI}$	Luo, 2004	Exponential	0.73
Fine sandstone	$\boldsymbol{\sigma_t=1.818CAI+1.401}$	**Present study**	**Linear**	**0.53**

Note: CAI: Cerchar abrasivity index; LA: Los Angeles abrasivity; EQC: Equivalent quartz content; σc: Uniaxial compressive strength; σt: Uniaxial tensile strength; σst: Saturated tensile strength

To conclude, we do not find a quantitative mathematical relationship between rock abrasivity and tensile strength, but the two are positively correlated. Therefore, we cannot obtain the value of one parameter from the other parameter by a mathematical formula in practical engineering. The reason is that besides mineral composition, rock abrasivity is also related to rock microstructure (fractures, veins, beddings, joints) and mode and intensity of cementation. Since rock abrasivity is controlled by various factors, we cannot establish a mathematical relationship by relating to only one factor.

6. Conclusion

Based on the above analysis, the following conclusions are drawn:

(1) Rock abrasivity and tensile strength are not quantitatively related through a specific mathematical expression. The two are only positively correlated in a qualitative sense. That is, the higher the tensile strength, the higher the rock abrasivity.

(2) Because rock abrasivity is controlled by various factors, we cannot establish a mathematical expression of rock abrasivity by relating to tensile strength alone. Besides tensile strength, rock abrasivity is also affected by contents of hard minerals (i.e. EQC) and the mode and strength of mineral bonding (crystallization and cementation). Moreover, during construction, the factors of mechanical properties, mineral composition and texture of the rocks should be also taken into account. The choice of cutting head of TBM is related to crustal stress of the construction site as well.

(3) Rock abrasivity is more correlated with tensile strength than with mineral composition, since the two are both influenced by multiple factors. As indicated by construction experience, the higher the mechanical strength, the higher the rock abrasivity will be. Although mineral composition also influences rock abrasivity, the specific rock abrasivity varies greatly with cementation type and crystallization morphology. Therefore, we should be cautious when deriving rock abrasivity from EQC.

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