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Relationship between brittleness of rock, CAI and cutting performance of a TBM disc cutter

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ABSTRACT

Brittleness of rock is known to be an important factor affecting the fragmentation characteristics in mechanized rock-cutting. As the interaction between cutting tool and rock (i.e., cutter forces, cutting efficiency, and abrasiveness) in mechanical cutting is strongly influenced by the rock fragmentation, the cutting tools (i.e., disc cutter and pick cutter) experience different cutting behaviors depending on the rock brittleness. In this study, the relationships between brittleness of rock and abrasiveness of rock, and cutting efficiency of a TBM disc cutter were investigated for the Korean rock types. The brittleness was calculated by the relations between uniaxial compressive and Brazilian tensile strengths. The cutting efficiency and abrasiveness were evaluated by specific energy from linear cutting machine (LCM) test and Cerchar abrasiveness index (CAI) test, respectively. The results show that the brittleness has significant correlations with the cutting efficiency and CAI value.

1. INTRODUCTION

Selecting of an appropriate excavation method and estimations on excavation performances and cutter wear are important tasks in the early stage of TBM tunneling project. Various rock properties are used to evaluate the cutting performances and cutting tool life. Of the rock properties, brittleness of rock is known to be an important factor affecting the characteristics of rock cutting. There is no universal agreement on the measurement and definition of brittleness of rock. In many previous researches (Hucka and Das, 1974; Kahraman and Altindag 2004; Tiryaki, 2006; Gong and Zhao,

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2007; Yagiz, 2009; Jeong et al., 2016), brittleness of rock is usually defined by indirect measurements, i.e., the mathematical relations between uniaxial compressive and Brazilian tensile strengths of rock as follows:

$$B_1 = \frac{\sigma_c}{\sigma_t} \quad (1)$$

$$B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \quad (2)$$

$$B_3 = \sqrt{\frac{\sigma_c \times \sigma_t}{2}} \quad (3)$$

where B_1, B_2, and B_3 are the brittleness indices, σ_c is the uniaxial compressive strength of rock (in MPa), and σ_t is the Brazilian tensile strength of rock (in MPa).

The specific energy is defined by required energy to excavate unit volume of rock mass, thus is a representative index to identify the cutting efficiency of a cutting tool and mechanical excavators (Jeong and Jeon, 2018). The optimum cutting condition (or optimum cutter spacing) is defined where the specific energy is minimized under given rock type, and the SE at the optimum cutting condition can be used to simply estimate excavation rate of a TBM as following equation.

$$\mathrm{ICR} = k \times \frac{P}{SE} \quad (4)$$

where ICR is instantaneous cutting rate (m^3/h), k is the energy transfer ratio typically changing between 0.7 and 0.8, P is the power consumed during the excavation, and SE is the specific energy at the optimum cutting condition which is obtained from the rock cutting tests or empirical equations. Therefore, identifying optimum specific energy for a given rock formation and cutting condition is one of the most important tasks in the preliminary design phase of the TBM tunneling.

While, abrasiveness of rock is important issue that is directly related to cutting tool consumption during tunnel excavation work. Although there are many suggested methods to determine abrasiveness of rock, Cerchar abrasiveness index (CAI) test is one of the most common testing methods to estimate abrasives of rock. The test measures rock abrasiveness for determining cutter life and consumption. Due to the simplicity and economic advantages of the test, the CAI test is increasingly being used as a method to assess the abrasiveness of rock in many mining and tunneling machine applications.

This study summarized linear cutting machine tests and Cerchar abrasiveness tests that were conducted for the Korean rocks so far. Also, we investigated the relationship between the different concepts brittleness of rock, cutter force, the specific energy, and CAI, which are importation design parameters in TBM tunneling. In particular, the results of the LCM test and the CAI test conducted on Korean rocks up to now were collected and used for the analysis. Using the database, this study aims to find some empirical correlations

2. STATISTICS OF DATABASE

This study collected results of LCM tests and Cerchar abrasiveness tests for Korean rocks from the previous studies (Cho et al., 2010, Jeong et al., 2011, Lee et al., 2012, KICT, 2014).

2.1 Linear cutting machine (LCM) test

Full-scale cutting test is known well as linear cutting machine test (LCM test). Large rock specimen is required to carry out the LCM test with real size disc cutter (usually 12 – 20 inches in diameter). Because real disc cutter is used in the test, acting forces (i.e. normal, rolling, side forces) on a disc cutter during excavation, optimum cutter spacing (s/p ratio), cutting efficiency, and other operational parameters can be directly determined from the test. In Korea, the LCM system was also built with 200 tons loading capacity, three-directional servo controlled loading system at Korea Institute of Construction Building Technology (KICT) in 2005 (Figure 1).

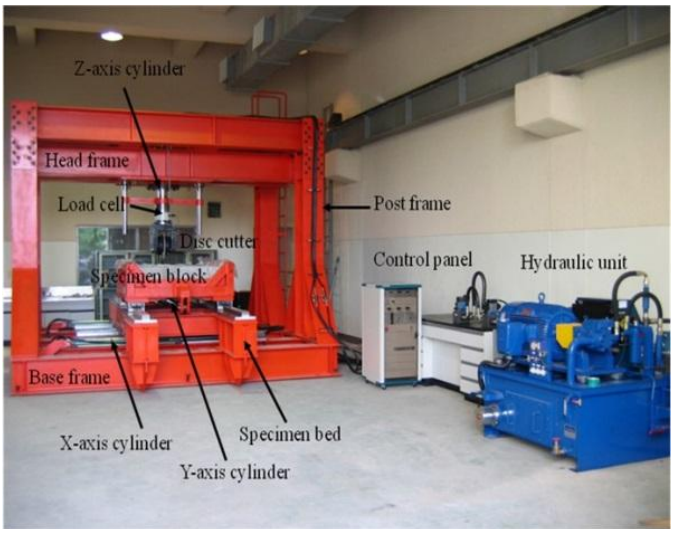


Fig. 1 The linear cutting machine system (KICT, 2004)

Also, a series of the LCM tests has been performed for Korean rocks for the past decade or so. Table 1 shows the mechanical rock properties and brittleness indices of the Korean rocks used for LCM tests. The database includes 8 igneous rocks, 5 metamorphic rocks, and 2 sedimentary rocks. Uniaxial compressive strengths of the rocks vary from 36.5 – 241.0 MPa, and Brazilian tensile strengths vary from 4.7 – 25.2 MPa

Table 1. Mechanical properties of rocks used in the LCM tests

Rock type	UCS (MPa)	BTS (MPa)	B_1	B_2	B_3
Granite #1	209.0	9.2	22.71	0.915	31.01
Granite #2	91.3	10.1	9.06	0.801	21.43
Granite #3	107.6	7.4	14.48	0.871	19.99

Granite #4	135.3	6.8	19.93	0.904	21.43
Granite #5	36.5	4.7	7.71	0.770	9.28
Granite #6	145.5	7.8	18.65	0.898	23.82
Diorite	158.5	11.2	14.15	0.868	29.79
Felsite	145.5	9.5	15.31	0.877	26.28
Gneiss #1	167.5	10.6	15.80	0.881	29.79
Gneiss #2	91.5	15.2	6.03	0.715	26.35
Gneiss #3	123.8	11.2	11.02	0.833	26.36
Gneiss #4	241.0	13.3	18.05	0.895	40.10
Gneiss #5	186.0	11.5	16.12	0.883	32.76
Tuff	115.5	25.2	4.58	0.642	38.14
Limestone	63.6	8.86	7.18	0.756	16.78

Table 2 also summarizes the LCM test results with the Korean rocks (Cho et al., 2010; Jeong et al., 2011; KICT, 2014), and the cutting tests were made by a CCS disc cutter with 17 inch (432 mm) of diameter. Also, the LCM results were selected at optimum cutting conditions for the statistical analysis. In the LCM tests, the optimum s/p ratio was found between 7.5 and 18.0, and the cutter forces were measured as average values. Boreability index (in kN/mm) is defined by the required normal force to penetrate unit depth (in mm) of rock, it is often called as field penetration index (FPI) in previous study (Hassanpour et al. 2010).

Table 2. Results of linear cutting machine test for Korean rocks

Rock type	p^* (mm)	S_{opt}^* (mm)	MNF** (kN)	MRF** (kN)	SE_{opt}^* (kWh/m^3)	BI* (kN /mm)
Granite #1	4	40	122.0	5.8	4.17	30.50
Granite #1	6	60	184.2	10.1	3.76	30.70
Granite #1	8	60	212.5	17.2	3.50	26.56
Granite #2	4	48	74.0	5.6	3.20	18.50
Granite #3	4	40	90.8	5.5	3.46	22.70
Granite #4	5	70	171.3	2.6	0.74	34.26
Granite #5	4	72	32.9	4.2	1.46	8.23
Granite #5	6	108	55	6.9	1.06	9.17
Granite #5	8	144	62.4	8.0	0.69	7.80
Granite #6	3	75	75.1	3.7	1.64	25.03
Granite #6	5	75	85.7	2.6	0.69	17.14
Granite #6	7	75	94.8	8.4	1.60	13.54
Diorite	5	70	126.2	14.1	4.03	25.24
Diorite	7	70	129.8	17.7	3.61	18.54
Felsite	5	70	94.6	9.2	2.63	18.92
Felsite	7	90	180.6	21.4	3.40	25.80
Gneiss #1	5	70	119.7	11.1	3.17	23.94
Gneiss #2	4	48	89.7	7.8	4.08	22.43
Gneiss #3	4	60	63.2	5.5	2.28	15.80
Gneiss #4	4	60	103	7.2	4.22	25.75

Gneiss #4	6	60	127.1	9.4	3.87	21.18
Gneiss #4	8	80	165.4	17.8	3.38	20.68
Gneiss #5	4	30	61.5	2.6	2.57	15.38
Gneiss #5	6	45	84.8	5.2	2.85	14.13
Tuff	4	60	65.6	4.3	1.79	16.40
Limestone	2	36	41.4	1.6	2.22	20.70
Limestone	4	72	63.6	4.7	1.62	15.90

** P, S_{opt},SE_{opt}, and BI are penetration depth, optimum cutter spacing, specific energy, boreability index at optimum cutting condition, respectively.*
*** MNF and MRF were mean normal force and mean rolling force, respectively.*

2.2 Cerchar abrasiveness index test

There are two kinds of testing equipment, original Cerchar equipment and West Cerchar equipment. Original Cerchar equipment has a moving pin lever with fixed rock specimen on the other hand, rock specimen travels under the fixed stylus pin in West Cerchar equipment. In this study, West Cerchar equipment is adopted. The stylus pin have 90° tip and diameter of 10 mm and be made of steel with specific Rockwell Hardness. Suggested hardness of stylus pin (HRC 55) was used for the tests referred to ASTM standard (D-7625-10 2010).

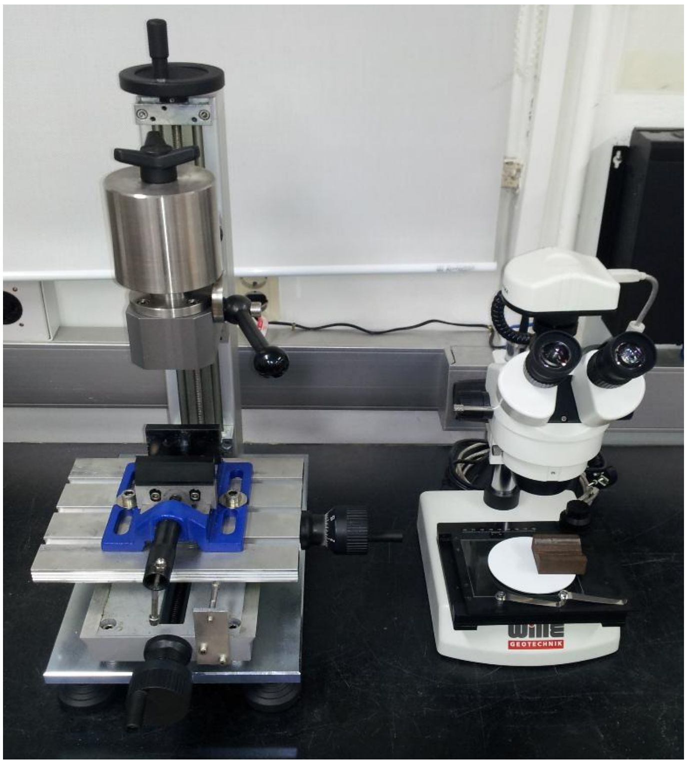


Fig. 2 Cerchar abrasiveness test system in Korea

Table 3 summarizes the Cerchar abrasiveness test results with Korean rocks, some testing results were also presented in the previous study (Lee et al., 2012). The database includes 14 igneous rocks, 11 metamorphic rocks, and 5 sedimentary rocks.

Uniaxial compressive strengths of the rocks vary from 34.9 – 235.3 MPa, and Brazilian tensile strengths varies from 1.6 – 18.2 MPa.

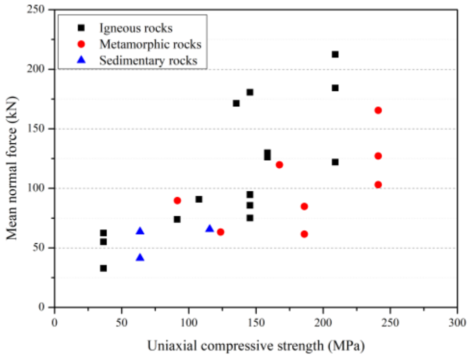
Table 3. CAI values and mechanical properties of Korean rocks

Origin	Rock type	UCS (MPa)	BTS (MPa)	EQC	CAI	B_1	B_2	B_3
Igneous	Granite #1	178.4	8.2	58.3	3.001	21.75	0.912	27.06
	Granite #2	145.9	7.8	64.1	2.753	18.61	0.898	23.92
	Granite #3	135.3	6.8	43.0	2.688	19.93	0.904	21.43
	Granite #4	170.9	9.0	64.5	2.902	19.08	0.900	27.67
	Granite #5	176.7	8.3	59.5	3.061	21.43	0.911	26.99
	Granite #6	151.3	10.2	64.0	2.410	14.89	0.874	27.72
	Granite #7	173.6	6.9	59.1	2.555	25.20	0.924	24.45
	Granite #8	121.5	6.2	62.4	3.184	19.77	0.904	19.33
	Granite #9	163.6	9.8	63.6	3.217	16.65	0.887	28.35
	Granite #10	34.9	1.6	61.7	2.599	22.22	0.914	5.24
	Diorite	235.3	14.8	36.6	2.658	15.86	0.881	41.78
	Gabbro	110.0	7.8	38.3	2.625	14.03	0.867	20.77
	Diabase	234.5	14.2	39.4	2.658	16.58	0.886	40.73
	Porphyry	195.6	14.3	44.6	2.422	13.65	0.863	37.43
Metamorphic	Gneiss #1	126.9	7.5	6.6	0.690	15.41	0.878	26.28
	Gneiss #2	162.7	17.5	47.3	2.208	15.70	0.880	29.75
	Gneiss #3	125.3	9.1	30.4	1.286	5.60	0.670	20.64
	Gneiss #4	115.8	17.8	70.7	2.683	17.91	0.894	27.11
	Gneiss #5	65.6	13.0	52.2	2.708	12.23	0.849	45.10
	Gneiss #6	162.2	9.1	81.2	2.946	9.34	0.807	35.45
	Gneiss #7	223.1	18.2	50.8	2.792	13.94	0.866	27.95
	Gneiss #8	173.6	6.9	59.1	2.555	16.57	0.886	31.22
	Gneiss #9	153.1	16.4	51.1	3.030	12.66	0.854	30.45
	Amphibole	121.5	6.2	62.4	3.184	22.36	0.914	26.89
	Propylite	163.5	9.8	63.6	3.217	13.48	0.862	30.61
Sedimentary	Dolomite	147.5	10.6	73.0	2.346	13.17	0.859	24.08
	Limestone	34.9	1.6	61.7	2.599	16.97	0.889	21.79
	Sandstone	179.7	10.9	50.7	2.613	9.30	0.806	37.72
	Shale	153.2	12.1	55.6	2.744	13.85	0.865	23.82
	Tuff	179.8	8.0	47.8	2.799	6.50	0.733	32.14

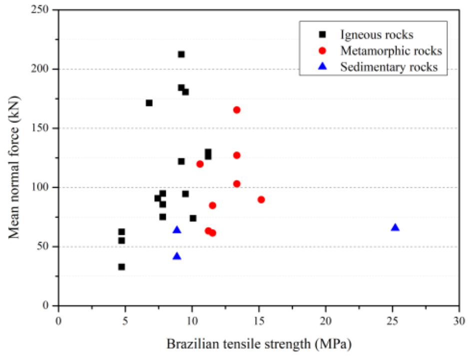
3. CORRELATION WITH BRITTLENESS OF ROCK

3.1 Cutter force

UCS and BTS are basic input parameters to estimate cutter forces in empirical TBM performance prediction model. Figures 3 and 4 shows the relationship between MNF, UCS and BTS. However, the cutter forces are highly affected by the penetration depth of a disc cutter. Thus, the relationships shown in figures 3 and 4 were somewhat scattered because different penetration depths are considered.

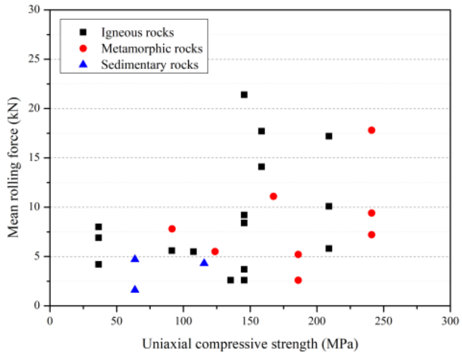


(a) UCS

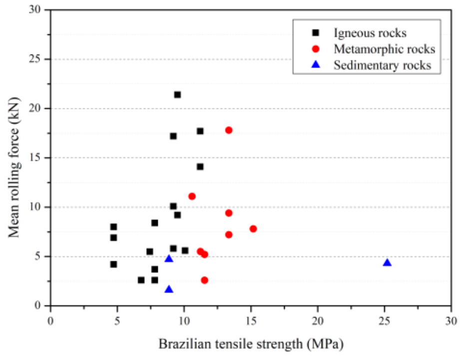


(b) BTS

Fig. 3 Relationship between mean normal cutter force and rock strengths



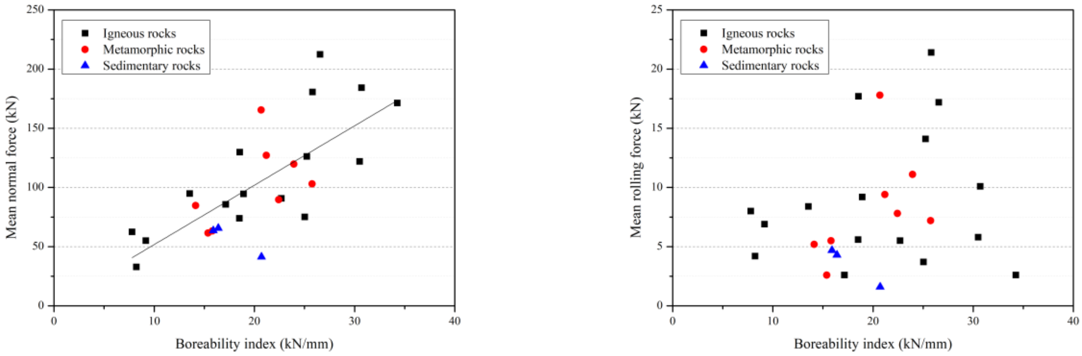
(a) UCS



(b) BTS

Fig. 4 Relationship between mean normal rolling force and rock strengths

In order to diminish the effect of penetration depth, boreability index (BI) facilitates quantitative analysis for the relations between rock strengths and cutter forces. Figure 5 shows the relationship between BI and cutter forces, and significant linear relations were found in case of normal force. However, rolling force had poor correlation with BI. The rolling force is usually estimated based on the empirical relationship between the normal force and rolling force. The relationship can be expressed as concept of cutting coefficient, which is defined by the ratio of cutting force to normal force, and it was found to be 0.08 on average, for all Korean rock types.



(a) MNF (b) MRF

Fig. 5 Relationship between mean cutter forces and boreability index

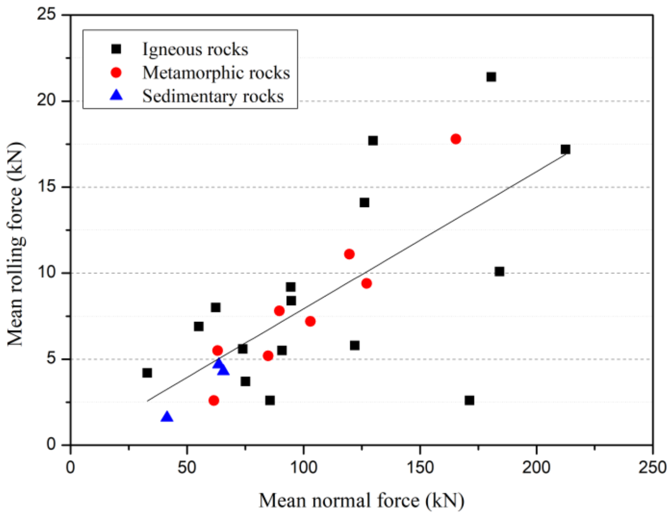
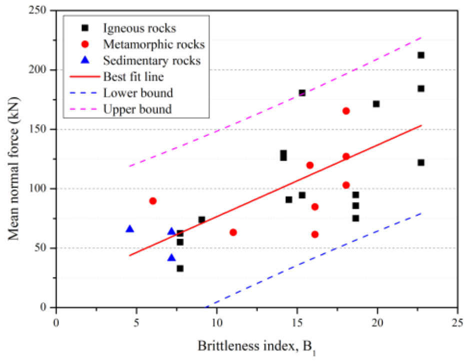
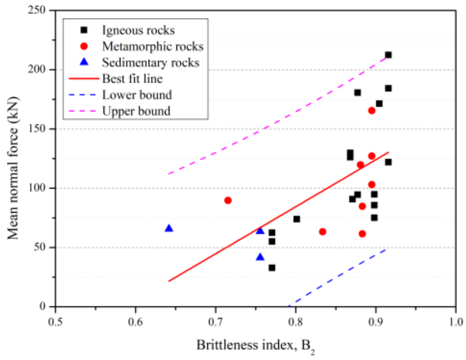


Fig. 6 Result of Cutting coefficient (CC) obtained from LCM test

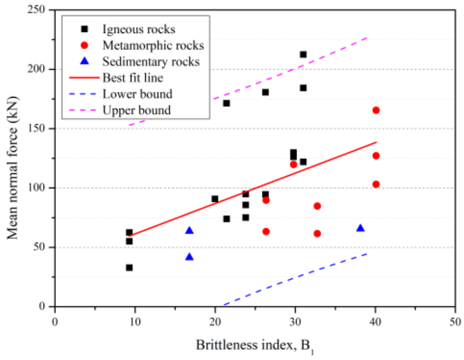
Based on the basic relationships, we attempted to find correlations between cutter forces and brittleness indices which are defined by UCS and BTS. Figure 7 shows that brittleness indices were highly correlated with the normal cutter force, and prediction bands (upper and lower bound) were also given under 95% of confidence level. Among these brittleness indices, B_1 shows the best correlation with MNF. As the definition of B_2 and B_3, the effect of tensile strength on brittleness is underestimated in case of B_2, otherwise B_3 always increase with the rock strengths. In rock cutting, the tensile strength is of importance in rock fragmentation process because rock chipping highly depends on the tensile cracks propagates towards adjacent cutting lines. The characteristics of the indices lead the lower correlation with the cutter force.



(a) B_1



(b) B_2



(c) B_3

Fig. 7 Relationships between brittleness indices and mean normal force

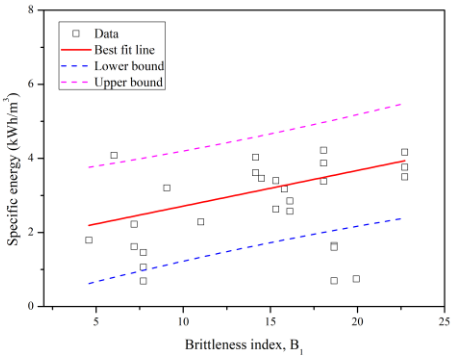
Prediction models for the cutter forces obtained from statistical regression analysis are summarized in Table 4. For generalized force prediction, penetration depth and cutter spacing of a disc cutter were taken account into the force prediction equations. Based on the results, B_1, UCS, and BTS give better prediction for the cutter force as input parameters than other brittleness indices. And it is confirmed that UCS has positive relation with cutter force, while BTS has negative relation with the cutter force. Also, if it is not possible to perform LCM test for given rock formation in the early stage design of TBM tunneling, the cutter force, an essential parameter for specification design of TBM, can be approximately estimated by using basic rock properties, i.e., the brittleness or rock strengths.

Table 4. Prediction models for cutter normal force

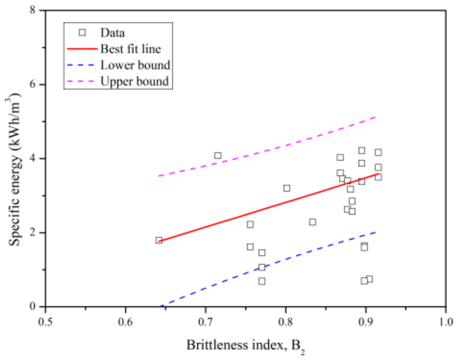
Input parameters	Equations
B1, p, S	$\mathrm{MNF} = p^{0.58} \times S^{0.27} \times {B_1}^{0.95}$ ($R^2 = 0.67$)
B2, p, S	$\mathrm{MNF} = 59.33 \times p^{0.69} \times {B_2}^{4.2}$ ($R^2 = 0.63$)
B3, p, S	$\mathrm{MNF} = p^{0.74} \times S^{0.29} \times {B_3}^{0.67}$ ($R^2 = 0.56$)
UCS, BTS, p, S	$\mathrm{MNF} = p^{0.77} \times S^{0.23} \times UCS^{0.78} \times BTS^{-0.47}$ ($R^2 = 0.71$)

3.2 Specific energy

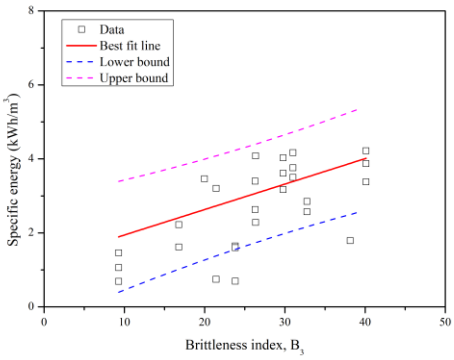
Figure 8 shows relationship between the uniaxial compressive strength and specific energy at optimum cutting conditions. For three brittleness indices, specific energy tends to increase with brittleness index. Among three indices, B_1 and B_3 has good linear correlations with the specific energy, while B_2 had poor correlation with the specific energy.



(a) B_1



(b) B_2



(c) B_3

Fig. 8 Relationship between the specific energy and brittleness indices

It is fact that the specific energy generally increases with rock strength because the required cutter forces increase with the strength. Figure 9 presents the relationship between UCS and the specific energy, and it shows better linear relationship than brittleness index. It means that the previous definition of brittleness does not sufficiently account for the relationship with the specific energy compared to when UCS is only considered.

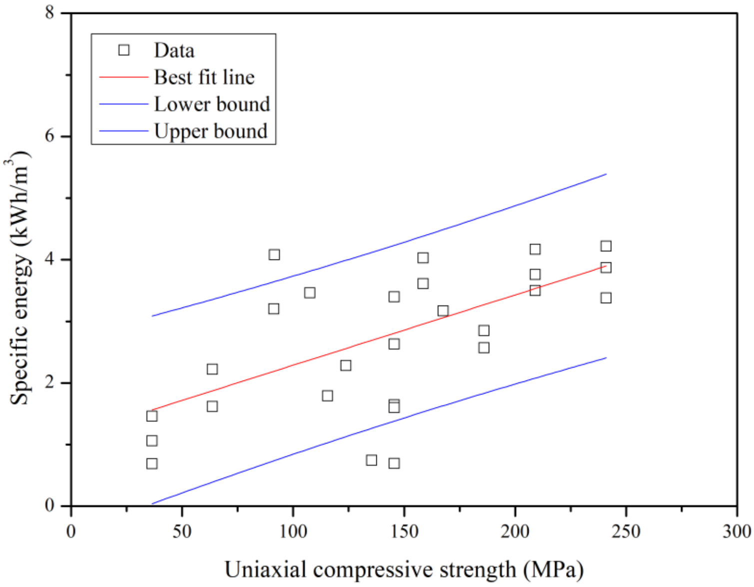


Fig. 9 Relations between UCS and specific energy

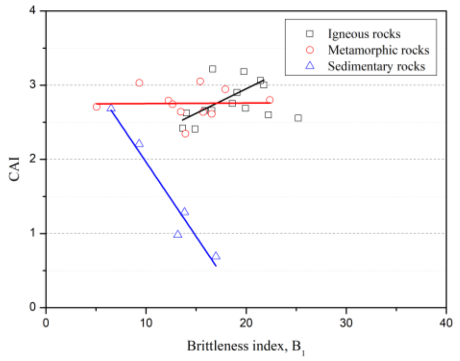
In table 5, Prediction models for the specific energy obtained from statistical regression analysis. For B_1 and B_2, there is no meaningful prediction model using multiple regression analysis. Based on the results, B_3, UCS, and BTS can be used to estimate the specific energy. And it is confirmed that UCS and BTS had positive relation with the specific energy, while cutter spacing and penetration depth has negative relation with the specific energy. Also, if it is not possible to perform LCM test for given rock formation in the early stage design of TBM tunneling, the specific energy can be approximately estimated by using basic rock properties, i.e., the brittleness or rock strengths.

Table 5. Prediction models for specific energy

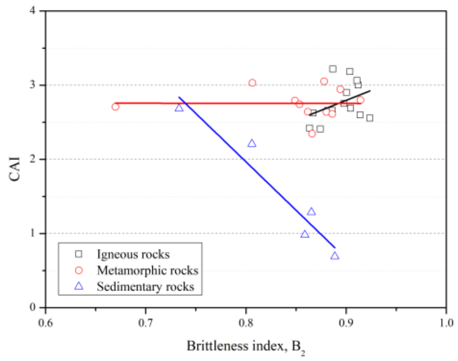
Input parameters	Equations
B3, p, S	$SE = 0.35 \times p^{-0.08} \times S^{-0.08} \times {B_3}^{0.77}$ (R^2 = 0.43)
UCS, p, S	$SE = 0.37 \times p^{-0.14} \times S^{-0.14} \times UCS^{0.56}$ (R^2 = 0.41)
UCS, BTS, p, S	$SE = 0.25 \times p^{-0.11} \times S^{-0.11} \times UCS^{0.50} \times BTS^{0.25}$ (R^2 = 0.45)

3.3 Abrasiveness of rock

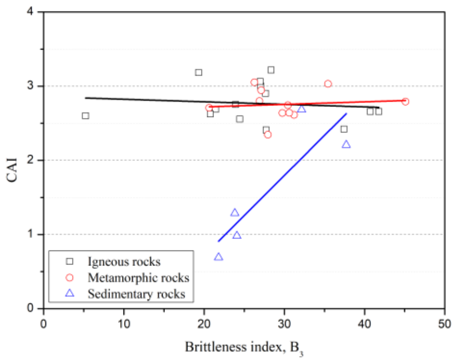
Figure 10 shows the relationship between CAI and brittleness index, the results were separated to their geological origins for clear relationship. For B_1 and B_2, CAI increases with the brittleness of rock in igneous rocks, while it decreases in sedimentary rocks. On the other hand, in case of B_3, CAI has no correlations with B_1 and B_2, but it has significant negative linear relations with B_3. This finding means that the relationship between the CAI and rock properties could be varied depending on the geological origin of rocks. Because main mineral composition depends on the origin of rocks, and it is thought that these differences in mineral composition leads to different trend in relationship between abrasiveness of rock and brittleness index. Also, the different relationships in current database meant that it is difficult to estimate rock abrasiveness with only brittleness of rocks.



(a) B_1



(b) B_2



(c) B_3

Fig. 10 The relationships between Cerchar abrasiveness index and brittleness indices

It is well known that equivalent quartz content (EQC) is highly correlated with the abrasiveness of rocks. Figure 11 shows the dependency of CAI on the EQC. The significant linear relationship was found between CAI and EQC. In table 6, regression models are given according to the geological origin of rocks. For igneous and sedimentary rocks, the equations based on individual relationships appear to be more reliable than those derived from the all rocks, while in case of metamorphic rocks, there is no reliable equations between CAI, brittleness, and EQC.

Table 6. Prediction models for Cerchar abrasiveness index

Input parameters	Equations
(All rocks)	$\mathrm{CAI} = 0.41 \times {B_1}^{0.07} \times EQC^{0.42}$ (R^2=0.78)
	$\mathrm{CAI} = 0.51 \times {B_2}^{0.25} \times EQC^{0.42}$ (R^2=0.77)
	$\mathrm{CAI} = 0.37 \times {B_3}^{0.01} \times EQC^{0.42}$ (R^2=0.77)

(Igneous rocks)	$\mathrm{CAI} = 0.41 \times {B_1}^{0.22} \times EQC^{0.32}$	(R^2=0.83)
	$\mathrm{CAI} = 0.98 \times {B_2}^{1.91} \times EQC^{0.32}$	(R^2=0.83)
	$\mathrm{CAI} = 0.60 \times {B_3}^{0.03} \times EQC^{0.36}$	(R^2=0.80)
(Metamorphic rocks)	not available in this study	
(Sedimentary rocks)	$\mathrm{CAI} = 2.58 \times {B_1}^{-0.60} \times EQC^{0.28}$	(R^2=0.97)
	$\mathrm{CAI} = 0.34 \times {B_2}^{-2.14} \times EQC^{0.34}$	(R^2=0.97)
	$\mathrm{CAI} = 0.05 \times {B_3}^{0.59} \times EQC^{0.42}$	(R^2=0.95)

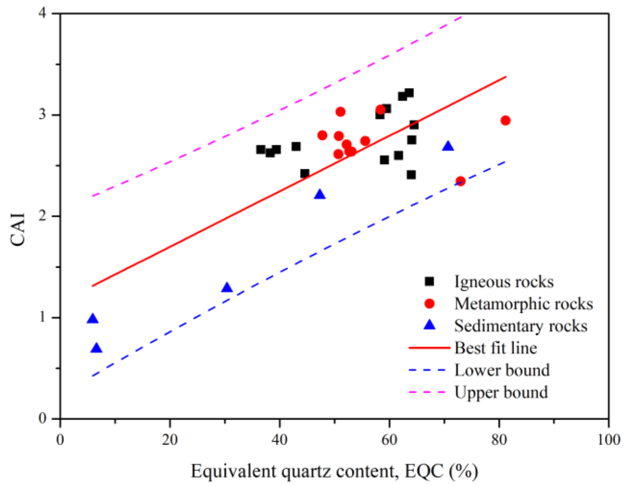


Fig. 11 The relationships between Cerchar abrasiveness index and equivalent quartz content

4. CONCLUSIONS

This study analyzed the correlation between the results of the LCM test and CAI test performed on Korean rocks, mechanical properties of rock, brittleness of rock. Based on the relationships, we presented several empirical equations for predicting cutter forces, specific energy, and CAI, which are important design parameters of TBM. Also, it is concluded that the parameters can be approximately estimated from the mechanical properties and brittleness of rocks. The main results and findings of this paper are as follows.

(1) Normal force of a disc cutter was correlated with uniaxial compressive and Brazilian tensile strengths of rocks, and it also has good linear relations with brittleness indices, especially B_1 has good linear relationships with normal force.

(2) While, there is no relationship between rolling force and brittleness index. The rolling force can be estimated using cutting coefficient and normal force, and cutting coefficient of Korean rocks was found as to be 0.08.

(3) Among three brittleness indices, optimum specific energy has good linear relationship with B_3, also, it is highly correlated with uniaxial compressive strength of rock. In addition, specific energy has positive relations with UCS, BTS, and brittleness indices, while it has negative relations with penetration depth and cutter spacing.

(4) CAI is correlated with the brittleness index, but in case of metamorphic rocks, there is no relationships between CAI and brittleness index. The correlation varied with the geological origin of rocks.

(5) CAI is highly correlated with equivalent quartz content. Significant linear relationship between CAI and EQC was found. Also, the CAI prediction models consisting of EQC showed high predictability.

Main results and findings of this study are thought to be useful references in determining excavation rates of machine, construction period, and cutting tool consumption with couple of rock properties in the preliminary design stage of TBM tunneling. In order to improve the reliability of the results, it is required to continuously expand the database. In future studies, the results will be compiled with the other database from foreign countries, and analyzed in depth.

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