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Effect of geomechanical properties on Cerchar Abrasivity Index (CAI) and its application to TBM tunnelling

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ABSTRACT

Abrasiveness of rocks plays an important role in the wear of TBM tunnelling. Cerchar Abrasivity Index (CAI) test is the most commonly used method to estimate rock abrasiveness due to its simple, fast test procedure and economic benefits. This study investigated the correlation between CAI and geomechanical properties of igneous and metamorphic rocks. Single and multiple regression analysis were performed and predictive models for the CAI from geomechanical properties were developed. It is found that single parameter alone is not suitable to predict the value of CAI. The result of the multiple regression analysis shows that quartz content is less influencing factor to predict the value of CAI. Also, the correlation between CAI and NTNU's Cutter Life Index (CLI) was examined and a predictive model for the CLI from CAI and geomechanical properties was suggested. Finally, the influence of CAI on disc cutter life prediction models was investigated and it was found that the variation of CAI has the maximum effect on the predicted disc cutter life in Gehring model.

1. Introduction

Abrasiveness of rocks plays an important role in the wear of TBM tunnelling. Wear takes place in not only excavation tools but also outside of the cutterhead and shield, screw conveyors on EPB TBMs, or slurry pipes, valves, and pumps on slurry TBMs. Several methods for estimating abrasiveness of rock have been developed. Cerchar Abrasivity Index (CAI) test is the most commonly used method to estimate rock abrasiveness due to its simple, fast test procedure and economic merits.

Many researches have been carried out to investigate the parameters affecting the results of CAI test. Atkinson et al. (1986) have shown various factors influencing the abrasiveness of rock. It included (a) mineral composition, (b) hardness of minerals, (c) shape and size of grain, (d) type of cementing material, and (e) geomechanical properties of rock such as strength, hardness and toughness. West (1989) proposed that quartz content (QC) is the main parameter influencing the CAI test. Plinninger et al. (2003) showed that the equivalent quartz content (EQC) alone is not suited to interpret the CAI value. Lee et al. (2013) found that equivalent quartz content is more affecting CAI value than quartz content itself.

Al-Ameen and Waller (1994) reported that CAI test is largely influenced by the rock strength. Deliormanlı (2012) also presented the rock strength has an effect on CAI value. Altindag et al. (2010) investigated the relation between brittleness and CAI value and found that CAI value is related with uniaxial compressive strength (UCS) and brittleness of rocks. Alber (2008) demonstrated that the CAI is stress-dependent. In his study, he conducted the CAI tests on samples in a triaxial cell and showed stress dependency for various rock types by higher CAI values upon confining pressure.

Lassnig et al. (2008) studied the impact of the size of grains on CAI value. It was found that there is no grain size dependency of the CAI value. Yaralı et al. (2008) studied sedimentary rocks and suggested that CAI value has a good linear relationship with quartz content, degree of cementing, equivalent quartz content, and quartz grain size.

Some research proposed a single parameter such as quartz content or rock strength as the main influencing parameter to CAI. On the contrary, others showed that the single parameter alone does not suit to interpret the value of CAI. It is worth noting the study of Barzegari et al. (2015). They developed a new soil abrasion testing system, Soil Abrasion Testing Chamber (SATC), to investigate the wear issue in soft ground TBM tunnelling projects. They concluded that SATC and CAI have good correlation and influenced

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by geological properties, environmental conditions and actual tunnelling parameters.

This study investigated the correlation between geomechanical properties of rocks and CAI. The geomechanical properties included quartz content, uniaxial compressive strength, Brazilian tensile strength, and brittleness index. The data were collected from the geological investigation base line reports (GIBRs) of various tunnelling projects in North America, Northern Europe, and East Asia. Also some data were obtained through literature reviews. Single and multiple regression analysis were performed and predictive models for the CAI from geomechanical properties were developed. The effect of the number of parameters on the multiple regression analysis was also investigated.

In addition, the correlation between CAI and the other abrasiveness index such as the NTNU's Cutter Life Index (CLI) was examined and a predictive model for the CLI from CAI and geomechanical properties was suggested.

Finally, CSM, NTNU, and Gehring models were employed to predict disc cutter life. The influence of CAI on those models was investigated by sensitivity analysis.

2. Cerchar Abrasivity Index

The testing method of Cerchar Abrasivity Index was invented in the mid 1980s in France in order to investigate the abrasivity of hard rocks.

The rock specimen is securely held in a vise and a steel pin is applied on the surface of a rock specimen under a load of 70 N and scratched on a distance of 10 mm. This procedure is repeated a minimum of five times in two scratching directions (perpendicular to each other) on the rock surface, always using a new or re-sharpened steel tip. The CAI is then calculated from the measured diameter of the resulting wear flat (in tenth of mm) on the testing steel pin. Fig. 1 shows the original design of Cerchar test apparatus (Alber et al., 2014).

In this study, the correlation between CAI and geomechanical properties of rocks including quartz content, uniaxial compressive strength, Brazilian tensile strength, and brittleness indexes were examined. The equivalent quartz content was not considered in this study since the number of collected data was very limited.

Brittleness is defined as a property of materials that break without significant deformation. It is usually considered one of the most important geomechanical properties of rocks. However, there is no standardized brittleness concept or accurate measurement method for the rock brittleness. Three different types of brittleness indices based on the compressive strength and tensile strength were employed in this study. B_1 and B_2 are proposed by Hucka and Das (1974), and B_3 is suggested by Altindag et al. (2010). The brittleness indices are given as follows:

$$B_1 = \frac{\sigma_c}{\sigma_t} \tag{1}$$

$$B_2 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t} \tag{2}$$

$$B_3 = \sqrt{\frac{\sigma_c \sigma_t}{2}} \tag{3}$$

where σ_c = uniaxial compressive strength (UCS) and σ_t = Brazilian tensile strength (BTS).

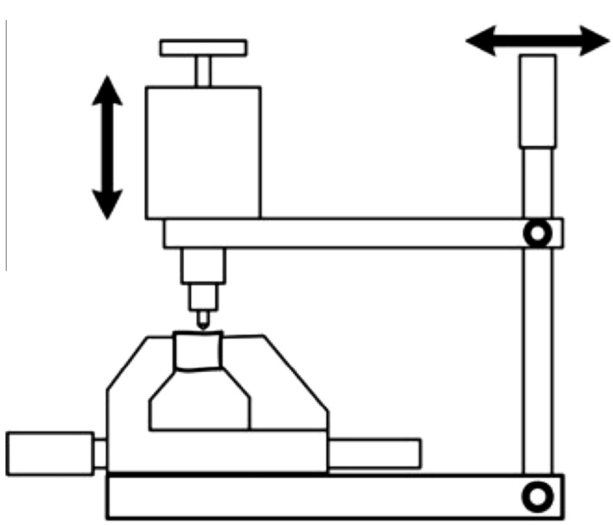

Fig. 1. Original design of Cerchar test apparatus.

A total of 535 data sets were found in literatures. All data sets were not contained the necessary geomechanical properties, thus the actual number of data sets employed in the analysis was less than 535. Rock types examined were from metamorphic and igneous origins. A total of 40 data sets were selected for igneous rocks and a total of 38 data sets were used for metamorphic rocks. The raw data used in the correlation analysis between CAI and geomechanical parameters are listed in Tables 1 and 2 for igneous and metamorphic rocks, respectively.

Figs. 2–8 show the distribution of geomechanical properties for igneous and metamorphic rocks. Some distributions of properties are similar to rock types, but the properties of QC, UCS, B_1, and B_3 give different distribution for rock types; the distributions of QC, UCS, B_1, and B_3 for igneous rocks show normal distribution, but in case of metamorphic rocks it is close to lognormal distribution.

3. Statistical analysis

3.1. Single regression analysis

Single regression with the independent variable of geomechanical properties and the dependent variable of CAI was performed. Figs. 9–14 show the relationships between CAI and quartz content, UCS, BTS, brittleness index B_1, B_2 and B_3 for different rock type, respectively. For igneous rocks, CAI increases with increasing UCS, brittleness index B_1, and B_2, and the coefficients of correlation are 0.24, 0.28, and 0.17, respectively. For metamorphic rocks, CAI increases with increasing UCS, BTS and brittleness index B_3. The coefficients of correlation are 0.48, 0.60, and 0.68, respectively. UCS is the common geomechanical property influencing CAI value for both rock types. In general, metamorphic rocks have better correlation between CAI and single geomechanical parameter than igneous rocks. The best correlation is obtained between CAI and brittleness index of B_3 for metamorphic rocks. There is no significant correlation between CAI and quartz content for both rock types. It can be inferred that quartz content alone is not suitable to predict the value of CAI.

3.2. Multiple regression analysis

In the multiple regression analysis response variable CAI depends on the explanatory variables of geomechanical properties. Both linear and non-linear models were considered in the multiple regressions. Linear models used the relationships between two or more explanatory variables and a response variable by fitting a linear equation to observed data. The linear equation can be expressed as:

$$Y = A + C_1X_1 + C_2X_2 + \ldots \tag{4}$$