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Investigating the effect of strength on the LCPC abrasivity of igneous rocks

Sair Kahraman*[1], Mustafa Fener[2a], Heiko Käsling[3b] and Kurosch Thuro[3c]

[1]*Mining Engineering Department, Hacettepe University, Ankara, Turkey*
[2]*Geological Engineering Department, Ankara University, Ankara, Turkey*
[3]*Engineering Geology Department, Technische Universität München, Germany*

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Abstract. The abrasivity of rocks results in tool wear in rock excavation or drilling projects. It can affect significantly the cost and schedule of the projects performed in abrasive rock massess. For this reason, the understanding of the mechanism of rock abrasivity is very important for excavation projects. This study investigates the effect of strength on the LCPC abrasivity coefficient (LAC) for igneous rocks. The LCPT test, the uniaxial compressive strength (UCS) and the Brazilian tensile strength (BTS) tests were carried out on the igneous rock samples. The abrasive mineral content (AMC) was also determined for each rock type. First, the LAC was correlated to the AMC and a very good correlation was found between the two parameters. Then, the multiple regression analysis was carried out by including the AMC, UCS and BTS to the analysis in order to infer the effect of the strength on the LAC. It was seen that the correlation coefficients of multiple regression models were greater than that of the relation between the LAC and the AMC. It is concluded that the AMC is the dominant parameter determining the abrasivity of rock. On the other hand, the rock strength has also significant effect on rock abrasivity.

Keywords: LCPC abrasivity; igneous rocks; rock strength

1. Introduction

The abrasivity of rocks always creates problem in drilling or excavation projects. The high cost due to cutting tool wear and downtimes due to the replacement of tools may highly influence the cost and schedule of the projects performed in rock masses. On the other hand, in the abrasive grounds, wear can also occur on several parts of the tunnel boring machine (TBM) such as front, rear and periphery of the cutterhead structure, bulkhead and plunging wall structures, and outlet devices (Nilsen *et al.* 2006 and 2007). Another important issue is that high rock abrasivity coincides frequently with higher rock strength. In such cases, the continuous application of high cutter load for the desired penetration will cause of bearing problems in discs. A failed bearing will lead to flattening of the disc at the face and the ensuing domino effect can cause a full wipe out of the cutters at the face in a very short time, if not detected/intercepted by the operator quickly. (Rostami 2016). Therefore, the understanding of the wear mechanism is important for the planning and cost estimation of projects.

The term “abrasiveness” describes the potential of a rock or soil to cause wear on a tool and the abrasive wear is the predominant wear process in most rock types (Plinninger *et al.* 2002). The abrasive wear is not only controlled by the abrasivity of rock. It depends on many factors (Verhoef 1997, Atkinson *et al.* 1986):

- Rock/soil properties (strength, hardness, fracture properties, brittleness, mineral composition, mineral hardness, grain shape and size, the type of matrix material)
- Tool characteristics (material properties, strength, hardness, geometry)
- Cutting process parameters (position of a tool with respect to rock penetration depth, rake and cutter angles, cutting velocity, cutting forces, heat generation, temperature, cooling).

Most researchers have focused on the influence of quartz content or equivalent quartz content (EQC) on rock abrasiveness. West (1989) stated that quartz content was the main parameter affecting the Cerchar abrasivity index (CAI). On the other hand, Plinninger *et al.* (2003) indicated that the EQC alone was not suited to assess the CAI value. Yarali *et al.* (2008) tested sedimentary rocks and showed that the CAI value had good linear relations with both quartz content and EQC. Lee *et al.* (2013) stated that the effect of EQC on the CAI was more than that of quartz content. Moradizadeh *et al.* (2016) investigated the relation between the EQC for ingenious, sedimentary and metamorphic rocks and found a good correlation between the two parameters. Ko *et al.* (2016) evaluated the relation between the CAI and quartz content for igneous and metamorphic rocks. They could not found significant correlations between CAI and quartz content for both rock types. Er and Tugrul (2016) found a strong correlation between the CAI value and quartz content for granitic rocks. Some researchers have also investigated the relation

∗Corresponding author, Professor
E-mail: sairkahraman@yahoo.com
[a]Associate Professor
E-mail: mfener@ankara.edu.tr
[b]Associate Professor
E-mail: heiko.kaesling@tum.de
[c]Professor
E-mail: thuro@tum.de

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between TBM cutter life and quartz content. Hassanpour et a. (2014) evaluated the TBM cutter consumption in the Karaj Water Conveyance Tunnel project and showed that quartz content alone did not show a good correlation with TBM cutter life. Ko *et al.* (2016) also did not found a correlation between cutter life index and quartz content. Literature review revealed that while some authors found correlations between rock abrasiveness and quartz content or EQC, others did not. Quartz content alone may not be a measure of tool wear or cutter consumption for some rocks, especially the rocks having some other abrasive minerals in addition to quartz.

In general, quartz content or abrasive mineral content is taken into consideration when evaluating the abrasivity of rock. However, in addition to abrasive mineral content rock strength may have important influence on the abrasivity of hard rocks. In this study, the effect of strength on the LCPC abrasivity coefficient (LAC) was investigated for igneous rocks.

2. Background

The LCPC abrasivity tets was developed by the Laboratoire Central des Pontset Chausées (LCPC) in France for testing rock and aggregates. The testing method is described in the French standard P18-579 (1990). Basic results of a comparison between the Cerchar Abrasivity and the LAC were performed by Buchi *et al.* (1995). They found that the correlation between the two methods was not good for all groups of rocks. Rocks with similar mineral compositions can lead to almost the same values in the case of the one test, in the other test they showed a considerable difference in their abrasivity class. Though igneous and metamorphic rocks indicated some form of linear correlation between the Cerchar Abrasivity and the LAC, sedimentary rocks showed a very poor correlation. Buchi *et al.* (1995) also carried out a limited number of tests in order to check the effect of using water in the LCPC test. Seven highly abrasive rock types were selected and 200 ml of fresh water with 500 g of crushed rock aggregate was used in the tests. A considerable increase in the LAC was observed with using water. The increase in the LAC values was attributed to the formation of thick abrasive slurry as a result of crushing of rock sample and mixing with water during the test.

Mathier and Gisiger (2003) carried out a study on olivine and theolite basalts. After combining their results with other researcher's data, they found a good correlation between Cerchar and LAC values. They stated that approximately one unit of Cerchar Index was equal to 300 g/t of LAC index. Fowell and Abu Bakar (2007) presented a review of the LCPC and the Cerchar Abrasivity measurement methods. They analyzed various factors influencing the results of the Cerchar test and the LCPC test and attempted to develop correlations between different test results by changing certain test parameters.

Käsling and Thuro (2010a) established a close linear correlation between the LAC and the Cerchar Abrasivity using the data from Büchi *et al.* (1995) and their own data. They also suggested a unified abrasivity classification for the Cerchar Abrasivity Index and the LAC by using the Cerchar Abrasivity Index as a basis. They stated that the LCPC abrasivity test becomes more and more common for rock and soil testing in Europe. They also expressed that ongoing work has been done to implement testing of soil and aggregates satisfying and testing recommendations for this test are also in preparation by the DGGT (Die Deutsche Gesellschaft für Geotechnik) working party.

The LCPC abrasivity test is only described for rock (Büchi *et al.*, 1995). However, coarse granular materials such as gravel and sand can have a significant impact on the wear of cutting tools and machine components. A detailed procedure of the LCPC abrasivity test for soil testing has been proposed in Thuro *et al.* (2007) and Käsling and Thuro (2010b). After performing a detailed research, they presented factors have to be considered for medium to coarse-grained soils. Käsling and Thuro (2010b) also presented a classification scheme for the LAC with allocation for different soil types. The absolute grain size is reflected in the "sharpness" of the grain size mixture prepared for the LCPC abrasivity test.

Drucker (2011) performed LCPC tests on the Danube gravel and discussed some factors influencing the abrasivity of granular materials. She showed that theLAC increased at a water content of 15% for fine gravel and sands. However, further addition of water decreased abrasivity. She indicated that fine-ground material resulted in damping effect on the wear rate. Regarding the grain size, she states that the interaction of different grain sizes in the abrasive material and the effect of a widely spaced grain size distribution on wear are still completely unknown.

Köhler *et al.* (2011) evaluated the data of 22 loose material samples (carbonate-crystalline fluvial gravel) from the Lower Inn Valley line and could not find a correlation between LAC and equivalent quartz content. The lack of the correlation is probably due to the fact that the equivalent quartz contents of the samples have a narrow range, about 35-60%.

Hashemnejad *et al.* (2012) investigated the effect of geological parameters on the LAC by testing calcite, orthoclase and quartz minerals. They studied the influences of shape, size and angularity of minerals, and the saturation rate of environment on the LAC. The results showed that increasing grain size and angularity increases the LAC. However, they found an inverse relation between shape effect and the LAC. The LAC decreases with increasing shape effect. They also demonstrated that saturation and the LAC had quadratic relation; the maximum LAC could be obtained as the saturation ranges from 25 to 40%.

After carrying out some tests on the prepared soil samples, Dullmann *et al.* (2014) stated that the equivalent quartz content has a decisive influence on the LCPC test results as long as other properties, which also affect the abrasiveness, remain constant. They also showed that increasing grain angularity increases abrasivity.

Abu Bakar *et al.* (2014) investigated the effects of reduced propeller speed on the LCPC abrasivity value by performing the tests at 2250 rpm and 4500 rpm, respectively. The test results showed that there is a good correlation between the LAC values at different rotational speeds.

Table 1 The physico-mechanical properties of the tested rocks

Rock code	Location	Rock type	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)
1	Kozak/Turkey	Granodiorite	121.8±3.9*	11.6±0.8
2	Kaman/Turkey	Syenite	89.6±11.6	6.6±0.6
3	Ortakoy/Turkey	Granite	114.5±4.3	9.0±0.7
4	Kaman/ Turkey	Granodiorite	84.9±9.5	8.0±1.3
5	Porrino/Spain	Granite	90.2±7.2	7.5±1.0
6	Unknown	Granite	120.3±6.3	14.8±1.1
7	Yesilburc-1/Turkey	Andesite	77.5±6.7	9.0±0.4
8	Yesilburc-2/Turkey	Andesite	65.8±4.8	5.5±0.7
9	Azatli/Turkey	Andesite	98.5±8.1	8.6± 0.9
10	Metten/Germany	Altered granite	74.2±5.1	5.7±0.8

*Standard deviation values

Table 2 Mineral contents of the tested rocks

Rock code	Quartz* (%)	Orthoclase* (%)	Plagioclase* (%)	Biotite (%)	Amphibole* (%)	Nepheline* (%)	Sphene* (%)	Pyroxene* (%)	Epidote (%)	Matrix (%)	AMC (%)
1	32	12	33	15	8	–	–	–	–	–	84
2	–	63	–	–	12	22	3	–	–	–	100
3	42	29	15	14	–	–	–	–	–	–	86
4	22	36	17	21	4	–	–	–	–	–	79
5	15	60	10	15	–	–	–	–	–	–	85
6	16	62	8	14	–	–	–	–	–	–	86
7	–	–	20	–	–	–	–	15	–	65	35
8	–	–	25	–	–	–	–	18	3	54	46
9	–	–	13	–	–	–	–	12	–	75	25
10	80	–	10	10	–	–	–	–	–	–	90

*Abrasive mineral

Kahraman *et al.* (2016) investigated the effects of textural properties of grains such as aspect ratio, roundness, and diameter on the LCPC abrasivity for coarse-grained igneous rocks. They concluded that the textural properties of loosened materials have a strong influence on the LCPC abrasivity, and thus, on the tool wear.

Recently, Cheshomi and Moradhaseli (in press), investigated the effects of petrographic characteristics on the abrasiveness of granitic building stones. They derived a strong linear relation between the LAC and equivalent quartz content.

3. Sampling and strength tests

Ten different igneous rocks were tested in this study, four of which were granites, three of which andesite, two of which were granodiorites, and one of which were syenite. Rock blocks were collected from the stone processing plants or field. The name and locations of the rocks are given in Table 1.

Test specimens were cored from the large blocks in the laboratory. After the cutting and grinding of the ends of cores, the uniaxial compressive strength (UCS) and the Brazilian tensile strength (BTS) tests were carried out according to the ISRM (2007) suggested methods. The averages of the test results are given in Table 1.

4. Mineralogical analysis

Thin sections were prepared from each rock in order to detect mineralogical components of them and mineral types were determined as percentages under the polarizing microscope. A point-counting device was mounted to the polarizing microscope for this purpose and mineral percentages were determined with precision. The minerals with Mohs' hardness of greater than 5 were accepted as abrasive, and indicated in Table 2. The total of abrasive minerals was described as abrasive mineral content (AMC). The mineral types, percentages of each mineral and AMC values are given in Table 2.

5. The LCPC abrasivity test

The LCPC abrasivity testing device consists of a 750 W motor which rotates a steel impeller (Fig. 1). The rectangular impeller is a metal plate of the size 50x25x5 mm and is made of standardized steel with a Rockwell hardness of HRB 60-75. 500g ±2 of air-dried rock sample, which was previously crushed to pieces of 4-6.3 mm diameters poured into the cylindrical vessel through the funnel tube. The metal impeller is rotated at 4500 rpm for 5 minutes in the cylindrical vessel with the sample rock.

For the abrasivity determination the steel impeller is weighed both before and after the LCPC test. LAC is defined as the ratio of the plate's weight loss to the mass of tested material and calculated as follows (Käsling and Thuro 2010a)

$$LAC = \frac{(m_0 - m)}{M} \quad (1)$$

where LAC is the LCPC abrasivity coefficient (*g*/*t*), *m*0 is the mass of impeller before test (*g*), *m* is the mass of impeller after test (*g*), and *M* is the mass of the sample material (= 0.0005*t*).

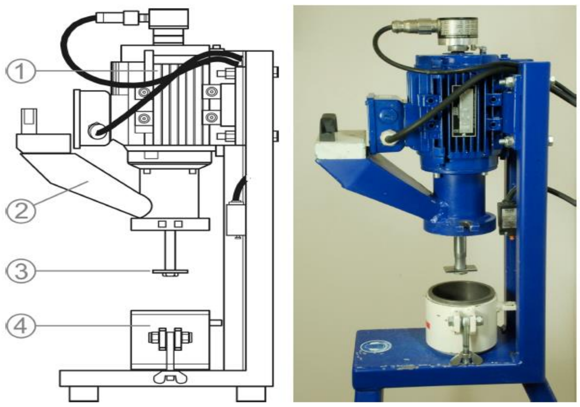

Fig. 1 LCPC abrasivity testing device: 1-motor, 2-funnel tube, 3-steel impeller, 4-sample container

Table 3 The average results of LACs

Rock code	LAC (g/t)	Abrasivity classification (Thuro *et al.* 2007)
1	1320±16.3*	Extremely abrasive
2	1567±9.0	Extremely abrasive
3	1433±9.4	Extremely abrasive
4	1313±9.2	Extremely abrasive
5	1327±9.8	Extremely abrasive
6	1437±4.7	Extremely abrasive
7	637±4.5	Very abrasive
8	470±12.0	Medium abrasive
9	680±19.0	Very abrasive
10	947±11.5	Very abrasive

*Standard deviation values

The block samples of rocks were first broken into small pieces by hand hammer. They were then fed into the jaw crusher. The crushed material was sieved to obtain 500 g test samples in the selected charging size range of 4-6.3 mm. The method of coning and quartering was applied for reducing the sample to 500 g. The LCPC abrasivity tests were carried out three times for each rock type. The average results of the tests are given in Table 3.

6. Results and discussion

The test results were evaluated using the regression analysis. First, the correlation between the LAC and the AMC was investigated. As shown in Fig. 2, a strong linear relation was found between the two parameters. The equation of the correlation and the correlation coefficient are as follows

$$LAC = 13.07\,AMC + 181.34 \qquad r = 0.87 \qquad (2)$$

where LAC is the LCPC abrasivity coefficient (g/t) and AMC is the abrasive mineral content (%).

It is seen from Fig. 2 that although some rocks have very similar AMC, they may have fairly different LAC values. This is probably due to the fact that the strength or other properties of these rock types are different from each other. In order to see the effects of the strength on the LAC, the LAC values were correlated to the UCS and BTS. As shown in Fig. 3, a correlation was found between the LAC and the UCS although it is not strong. A weak correlation was found between the LAC and the BTS (Fig. 4). However, this does not mean that the BTS has not influence on the LAC. This means that the effect of the BTS on the LAC is not dominant.

In order to reveal the effect of the strength on the LAC, multiple regression analysis was carried out by including the AMC, UCS and BTS to the analysis. The derived multiple regression models and the correlation coefficient are as follows

$$LAC = 11.20\,AMC + 7.59\,UCS - 400.81 \qquad r = 0.94 \qquad (3)$$

$$LAC = 12.65\,AMC + 41.06\,BTS - 147.98 \qquad r = 0.91 \qquad (4)$$

$$LAC = 11.08\,AMC + 8.30\,UCS - 5.56\,BTS - 410.76 \qquad r = 0.94 \qquad (5)$$

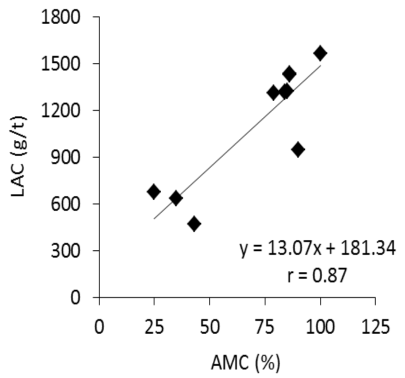

Fig. 2 The correlation between LAC and AMC

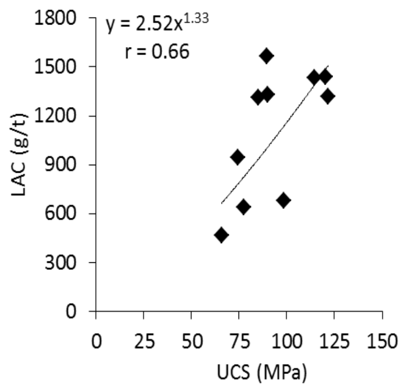

Fig. 3 The correlation between LAC and UCS

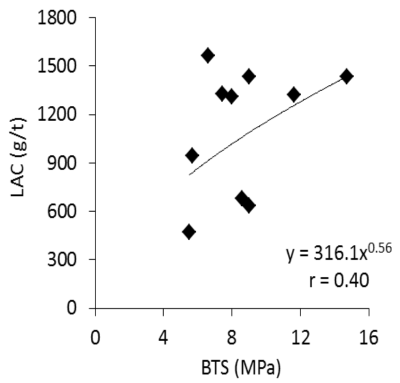

Fig. 4 The correlation between LAC and BTS

As shown in Eqs. (3)-(5), the correlation coefficients of multiple regression models are greater than that of Eq. (2). This reveals that the rock strength has a significant influence on the LAC.

The correlation coefficients of the Eqs. (2)-(5) are very high, but it does not necessarily identify valid model. The validation of the models should be further analyzed by using statistical tests such as t-test and F-test. The significance of r-values can be determined by the t-test, assuming that both variables are normally distributed and the observations are chosen randomly. The distribution of the data was checked by histogram analysis and the data didn't show normal distribution as shown in Figs. 5 and 6 given as examples. For this reason, t-test was not performed.

The significance of regressions was determined by the analysis of variance. In this test, a 95 % level of confidence was chosen. If the computed *F*-value is greater than tabulated

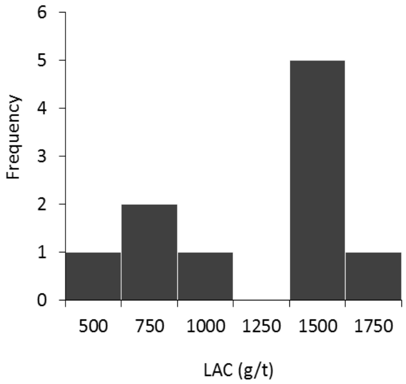

Fig. 5 Histogram plot for LAC

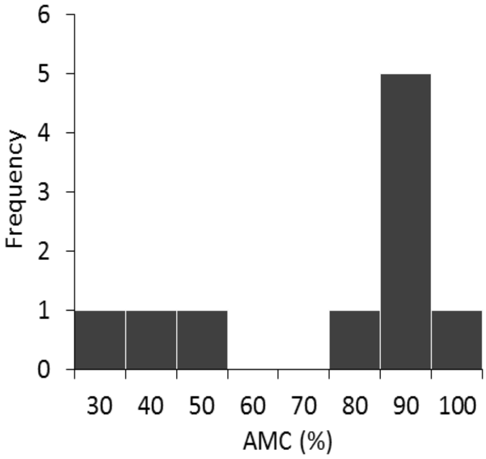

Fig. 6 Histogram plot for AMC

Table 4 F-test results

Equation no.	F-table	F-test
2	4.41	69.60
3	3.35	67.95
4	3.35	74.02
5	2.87	71.55

F-value, the null hypothesis is rejected that there is a real relation between the dependent and independent variables. The computed F-values are greater than the tabulated F-value as shown in Table 4. Therefore, it is concluded that the derived equations are valid according to the F -test.

7. Conclusions

In order to investigate the effect of strength on the LAC, igneous rocks such as granites, granodiorites, andesites, and syenite were tested and the results were evaluated. The findings of the study are as follows:

• A strong linear relation was found between the LAC and the AMC.

• The correlation coefficients of multiple regression models including the strength are greater than that of the relation between the LAC and the AMC.

• Because the AMC is the dominant factor for the rock abrasivity, rock strength has not much influence alone on the LAC.

Concluding remark is that the rock abrasivity is controlled firstly by AMC, but the rock strength has also significant influence on it. Further research is necessary to check the validity of the derived equations for the other rock types.

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