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THE EFFECT OF LIQUIDS ON MECHANICAL STRENGTH AND ABRASIVENESS OF ROCKS

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ABSTRACT: *Many methods of determining the abrasiveness of rocks were developed by a number of researchers. Although the effect of liquids on the mechanical properties of rocks has been investigated by some authors, the effect of liquids on the abrasivity of rocks has not been published. In this paper, the effect of different liquids on the abrasivity and mechanical strength of rocks was investigated. To achieve this goal; samples of sandstone, limestone and tuff were tested under laboratory conditions. The liquids having 4, 7.5 and 10-pH degrees were used in the experiments, representing acidic, alkaline and neutral conditions respectively. It was observed that the liquid which has a pH degree of 4 significantly increased the abrasivity of the above mentioned rocks. Compared with their dry values, the point load strength of the rock samples decreased when saturated with different liquids.*

KEYWORDS: *Abrasiveness, Point Load Strength, pH degree*

SIVILARIN KAYAÇLARIN AŞINDIRICILIKLARI VE MEKANİK DAYANIMLARI ÜZERİNDEKİ ETKİSİ

ÖZET: *Kayaçların aşındırıcılığının belirlenmesinde kullanılan bir çok yöntem çeşitli araştırmacılar tarafından geliştirilmiştir. Sıvıların, kayaçların mekanik özellikleri üzerindeki etkisi bazı yazarlar tarafından araştırılmış olmasına rağmen, sıvıların kayaçların aşındırıcılığı üzerindeki etkisi yayınlanmamıştır. Bu makalede, sıvıların kayaçların aşındırıcılığı ve mekanik dayanımları üzerindeki etkisi araştırılmıştır. Bu amaçla, kumtaşı, kalker ve tüf örnekleri laboratuvar şartlarında test edilmiştir. Deneylerde pH'ı 4, 7.5 ve 10 olan, sırası ile asidik, bazik ve nötr koşulları temsil eden, sıvılar kullanılmıştır. PH'ı 4 olan sıvının yukarıda bahsedilen kayaçların aşındırıcılıklarını önemli ölçüde arttırdığı gözlenmiştir. Sıvıya doygun hale getirilmiş kayaçların nokta yük dayanımları da kuru değerlerle kıyaslandığında azalmıştır.*

ANAHTAR KELİMELER: *Aşındırıcılık, Nokta yük dayanımı, pH derecesi*

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I. INTRODUCTION

The abrasivity of rocks plays an important role in mining operations such as excavation, drilling and loading. The more abrasive the rocks are, the higher the operation costs. In recent years, the studies on determining the abrasiveness of rocks have been carried out intensively. However, there is no universally accepted one standard test to determine the rock abrasivity although a large number of different tests are in use. Besides, all the studies about rock abrasiveness are concentrated on the amount of quartz, grain size and cementation degree of quartz, the geometry of the abrasive mineral and mechanical strength of rock. However, the effect of liquids on the abrasivity of rocks has not been investigated in the literature.

In this study, the effect of different liquids on the rock abrasiveness was investigated under laboratory conditions. Also, mechanical strengths of three different types of rocks, sandstone, limestone and tuff, were determined in order to investigate the effect of liquids on their mechanical strengths [1].

II. METHODS OF MEASURING THE ABRASIVENESS OF ROCKS

The methods that have been proposed for measuring the abrasiveness of rocks can be divided into two main groups as petrological and mechanical methods. The mechanical methods can be subdivided into two groups as tests using intact specimens of rock and tests using rock aggregate [2]. All related test methods are summarized in Table 1.

Table 1. Measuring methods of rock abrasiveness

		Brief description
Petrological Methods	1.Using Mohs' scale of hardness 2.Using Rosiwal's scale of hardness	In both systems, mineralogical composition is determined by petrological examination or X-Ray diffraction analysis.
	3. Quartz content	Determined from thin section or X-Ray diffraction.
	4. Silica content	Determined by chemical analysis of powdered rock.
Mechanical Methods	***Tests using intact rock specimens***	It depends on the application of metal tool of some sort to an intact rock specimen under controlled condition after which the wear of the tool is measured.
	1. Hacksaw test	Standard workshop reciprocating hacksaw is used.
	2. Tool wear test	A cylindrical rock specimen is cut in a lathe by a tool.
	3. Cerchar test	Wear flat of a steel cone is measured after the cone is passed across a rock specimen's surface under a load of 7.5 kgf.
	4. Modified Taber abrasion test	Taber Abraser machine is used for the test. The weight loss of the wheel is determined.
	Tests using rock aggregate	It depends on the interaction between a metal test piece of some sort and a sample of rock aggregate under controlled conditions.
	1. Steel plate test	Horizontal rectangular steel plate is rotated in cylindrical vessel containing a weighed quantity of crushed rock.
	2. Steel cube test	A one-inch bright mild steel cube is thumbled for three hours in a thumble-polishing machine together with a 900 gr sample of rock aggregate.

III. EFFECT OF LIQUIDS ON MECHANICAL STRENGTH

The result of the work of many authors has shown that moisture has a significant effect on the strength of rocks [3-20]. In most studies, it was reported that the mechanical strength of rocks decreased under saturated conditions. The effect of moisture content on the uniaxial strength of chalk was examined by Roxborough and Rispin [3]. They stated that compressive strength of chalk was less than 20 % of its dry strength in saturated condition. Similarly, the tensile strength fell by almost 80 % and shear strength by more than 70 %.

Kuznetzov [4] showed that the presence of liquids, especially water, substantially reduced the strength of rocks. The lower strength was attributed to the lowering of the surface free energy of the rock due to physical adsorption from the surrounding liquid; this is referred to as the "Rehbinder Effect".

Calback and Wiid, Boretti-Onyszkiewicz, Burshtein, Street and F.D. Wang reported that the compressive strength of sandstone decreased under saturated conditions when compared with that of dry conditions [5-8]. It was stated that the compressive strength of sandstone was inversely proportional to the surface tension of different liquids with which the specimen was saturated [5].

Dube and Singh studied the effect of humidity on tensile strength of five different types of sandstones [9]. Their results showed a decrease in strength ranging from 11 to 48 % under fully saturated atmosphere.

Obert et al, Price, Kjaernsli and Sande, Zaruba, Salustowicz, Feda, Simpson and Fergus conducted tests on various type of rocks with different percentages of moisture and reported a significant decrease in the strength of rocks with the increase in moisture content [10-16].

Vutukuri determined the effect of $AlCl_3$ solutions on the tensile strength quartzite [17]. He observed reduction in strength up to about 11 %. He also studied the effect of liquids on tensile strength of limestone and stated that since the surface free energy of a solid saturated with a liquid is a function of the properties (such as surface tension, dielectric constant) of the liquid, it can be postulated that the influence of the saturated liquid is to alter the surface free energy of the rock and hence its strength [18]. The greater the surface tension and dielectric constant of a saturating liquid, the lower the cohesion (hence the strength) between the particles making up the solid. Vutukuri found that as the dielectric constant and surface tension of the liquid increased, the tensile strength of the limestone decreased.

Boozer et al studied chemical effects of the fluids and found that chemically active fluids (water, oleic acid) reduced the strength of the rocks below the values obtained when similar specimens saturated with an inactive fluid (n-hexadecane) were tested under otherwise identical conditions [19].

Ojo and Brook studied the effect of moisture on compressive, tensile and point load strength of sandstone [20]. They observed that both compressive and tensile strength of sandstone decreased, but the effect of moisture on the tensile strength was greater than that on compressive strength. They also found a decrease in point load strength of 79 % from air dried to water saturated.

Although most authors reported that the strength of various rocks decreased when saturated with liquids, an increase in the strength of several rock types was also reported. Ruiz conducted tests on various types of rocks. The strength of some of basalt, diabase, granite, porphyritic granite, gneiss and limestone samples in saturated conditions were higher than the dry conditions. This was attributed to the heterogeneity of the rocks and to the small number of specimen tested [21].

IV. EXPERIMENTAL STUDIES

Water in an underground mine could be acidic, neutral and alkaline according to surrounding conditions of the mine. In order to predict the tool wearing behaviour of underground machines running under such conditions, laboratory tests which would be helpful in determining the effect of different liquids on the mechanical strength and abrasiveness of rocks were performed.

IV.1. Liquids Used In Laboratory Tests

The liquids having 4, 7.5 and 10 pH degrees were used in the experiments, representing acidic, neutral and alkaline conditions respectively. The pH degrees of these liquids were adjusted by means of a pH meter until the desired pH degree was reached. The liquid having a 4-pH degree was prepared by adding HCl into the distilled water. For the neutral liquid, distilled water was used without adding any chemical agent to the water, because the pH degree of distilled water was nearly 7.5. The liquid having a 10-pH degree was prepared by adding NaOH into the distilled water.

IV.2. Rock Samples Used In Laboratory Tests

Three types of rock samples were tested in this study. Namely; sandstone (Tunçbilek underground mine-Kütahya), limestone (Limestone quarry-Eskişehir) and tuff (Yazılıkaya region-Eskişehir).

Also, chemical analyses were carried out on the samples by grinding the samples under 100 mesh. The results of chemical analyses are given in Table 2.

Table 2. Chemical analyses of rocks used in tests

Rock	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)
Sandstone	46.77	6.23	9.37	7.43	7.50
Limestone	0.50	0.25	0.06	54.87	0.69
Tuff	73.65	12.41	0.62	2.38	0.38

IV.3. Steel Cube Test

This test was developed to predict the replacement rate of the disc cutter of full-face tunneling machines by determining the abrasiveness of rock debris produced by a full-face tunneling machine [2]. In this test, which is one of the mechanical methods using rock aggregate, a one-inch bright mild steel is thumbled for three hours in a thumble-polishing machine together with a 900 gr sample of rock aggregate. The loss in weight per hour of steel cube, expressed as a percentage of its original weight, is a measure of the abrasiveness of the rock. The higher steel cube abrasiveness index values indicate that the tested rock is more abrasive when compared with the rock having lower steel cube abrasiveness index.

Steel cube abrasiveness index is calculated by using following equation:

$$\text{SCAI} = \frac{\left(\frac{W_1 - W_2}{W_1} \cdot 100\right)}{3} \quad (1)$$

where;

SCAI : Steel cube abrasiveness index

W_1 : The weight of steel cube before test (gr)

W_2 : The weight of steel cube after test (gr)

In the sample preparation process; sandstone, limestone and tuff samples were crushed and screened to obtain 12.7-4.76 mm size fraction. Each rock aggregate in this size fraction, 900gr in weight, was saturated with liquids having 4, 7.5 and 10-pH degrees for 24 hours.

Prepared samples were thumbled together with one-inch bright ST-70 steel cube, having a Brinell hardness of 195, for three hours. For each test, a new steel cube was used and the weight of the steel cube was measured carefully both before and after the test. The loss in weight per hour of the steel cube was calculated by using Equation (1) for each type of saturated rock aggregate. The average results of 18 tests for each rock type, together with liquid adsorption percentages, are given in Table 3. In determining the liquid adsorption, 86 tests in total were performed.

Table 3. Liquid adsorption and steel cube abrasiveness index values

Rock and pH	Liquid adsorption (%)	Steel Cube Abrasiveness Index (10^{-4})
LimeStone		
pH=4	0.495	91.035
pH=7.5	0.369	64.19
pH=10	0.50	28.2
Sandstone		
pH=4	8.94	182.065
pH=7.5	9.34	95.18
pH=10	8.35	89.75
Tuff		
pH=4	18.34	52.025
pH=7.5	18.67	46.79
pH=10	18.85	31.845

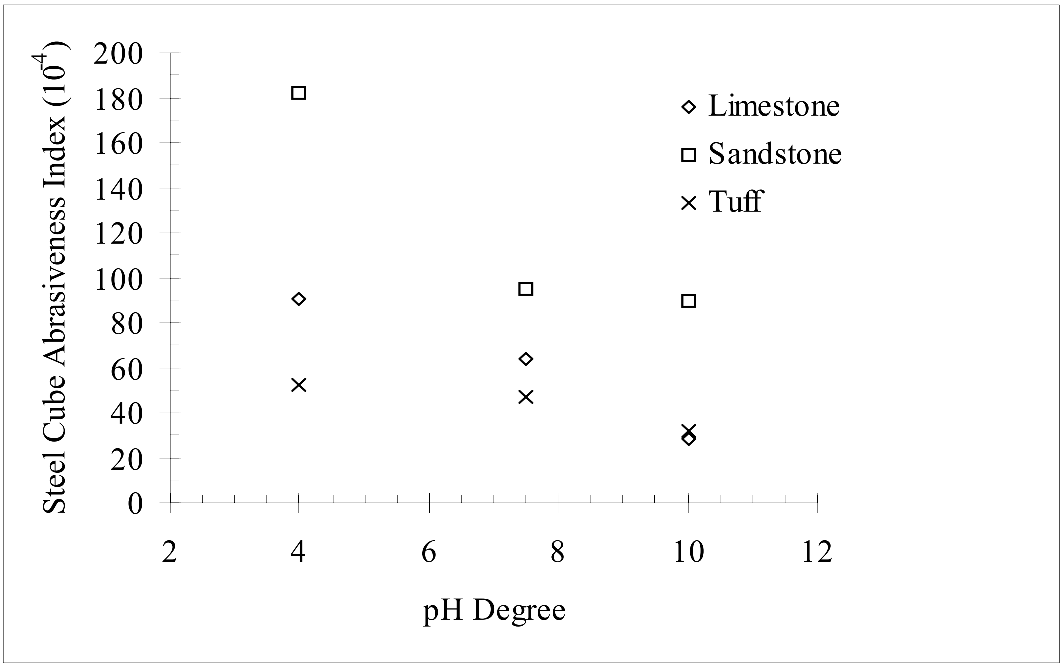

Figure 2. Steel cube abrasiveness index versus pH degree.

Relationships between the steel cube abrasiveness index and pH degree are shown in Figure 2. It can be seen from Figure 2 that steel cube abrasiveness indexes determined for 3 types of rocks decreased as the pH degree of liquids increased. It was also observed that the steel cube abrasiveness indexes of rocks saturated with acidic liquid were higher than those of saturated with neutral and alkaline liquids. The lowest values of steel cube abrasiveness index were obtained when the rocks were saturated with the alkaline liquid having pH-10 degree.

IV.4. Point Load Tests

The point load test is intended as an index test for the strength classification of rock materials [21].

In this study, axial point load tests were performed according to International Society of Rock Mechanics standards. Point load strengths of each type of rock were calculated for both dry and saturated samples. The calculated values and standard deviations are shown in Table 4.

Table 4. Point load strength of rocks

Rock	**Point load strength (MPa)**			
	Dry Samples *	***Saturated Samples*** **		
		pH=4	pH=7.5	pH=10
Limestone	7.04 ± 0.33	5.04 ± 1.36	2.26 ± 0.12	2.27 ± 0.24
Sandstone	1.34 ± 0.73	0.39 ± 0.08	0.39 ± 0.09	0.39 ± 0.20
Tuff	1.53 ± 0.16	0.73 ± 0.12	0.93 ± 0.15	0.70 ± 0.16
* Average of 30 tests ** Average of 86 tests				

It is obvious that the point load strength of all the tested rocks decreased when the rocks were saturated with liquids. But, the pH degree of the liquid did not affect the point load strength of the sandstone. However, the point load of the limestone at pH 7.5 and 10 decreased much more than the strength at pH 4 degree. Also, the point load of the tuff at pH 4 and 10 degrees decreased much more than the strength at pH 7.5 degree. These observed decreases in the point load of the rocks are given in Table 5.

Table 5. Decreasing ratios in point load strength

	Decrease in point load strength (%)		
	Limestone	Sandstone	Tuff
pH=4	28.41	70.10	52.29
pH=7.5	67.90	70.10	39.22
pH=10	67.75	70.10	54.25

The effect of liquids on the strength of rocks may be explained as follows:

Certain minerals decompose when they come in contact with liquids and are dissolved, creating more liquid-filled voids. The factor which contributes most in decreasing the strength of rocks seems to be the attack of liquids on crack tips, dissolving the material and increasing the stress at the apex, thereby helping in their propagation. It is also possible that liquids influence the surface energy of the rocks and its strength will depend upon the decrease or increase in the surface energy under the influence of the liquid since the creation of new surfaces during the process of fracturing is dependent upon the surface energy of the rock.

The relationships between the steel cube abrasiveness index and point load strength for limestone, sandstone and tuff samples are shown in Figure 3, 4 and 5 respectively.

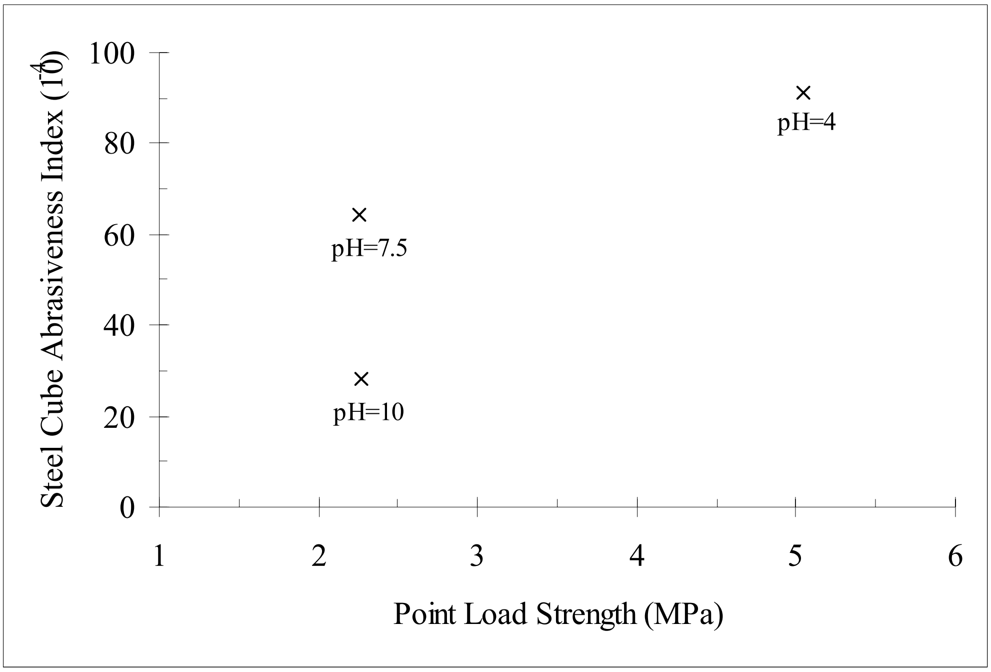

Figure 3. Steel cube abrasiveness index versus point load strength for limestone.

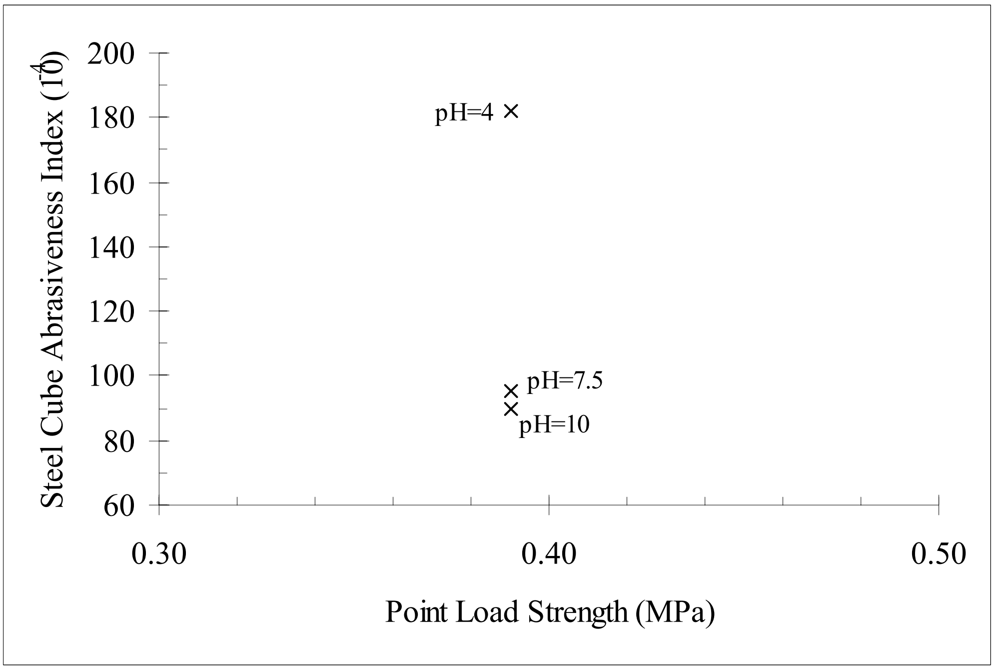

Figure 4. Steel cube abrasiveness index versus point load strength for sandstone.

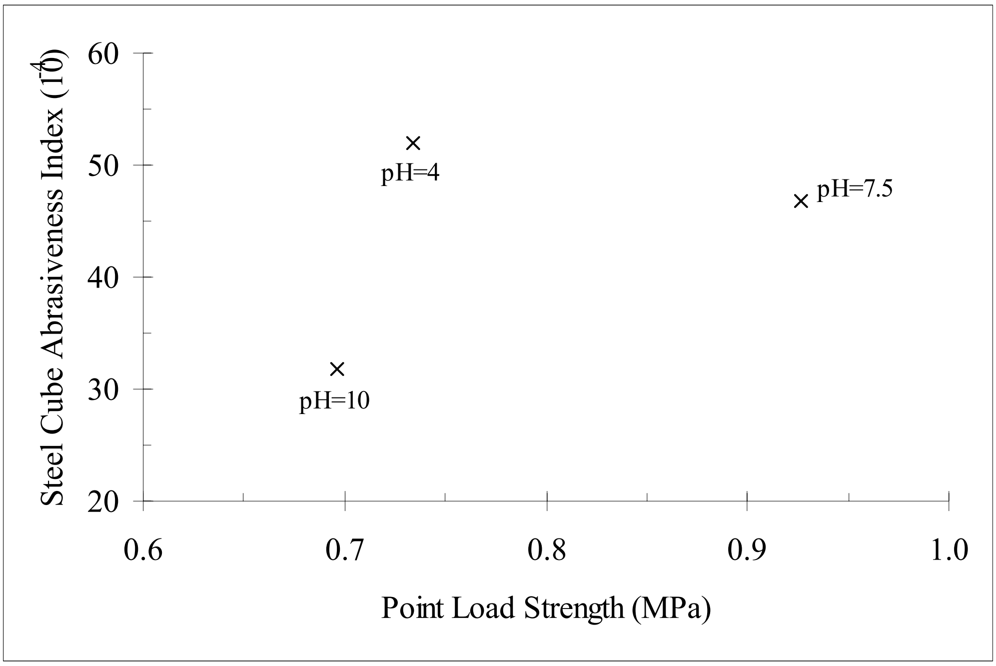

Figure 5. Steel cube abrasiveness index versus point load strength for tuff.

The highest abrasiveness index values for the rock samples were observed when the rocks were saturated with liquid having pH-4 degree. But, the point load strengths of the rocks were not the highest value at pH-4 degree. Although the point load of the sandstone did not change, the abrasiveness index was the highest value when compared with samples saturated with liquids having pH-7.5 and 10 degree. Similarly; while the point load strength of tuff samples at pH-4 degree was not the highest strength, it was observed that tuff samples at pH-4 degree had the higher abrasiveness index. So, it can be said that the steel cube abrasiveness index for tested rocks does not change linearly with the point load strength of the tested rocks.

V. CONCLUSIONS AND RECOMMENDATIONS

In order to investigate the influence of liquids on the strength and abrasiveness; limestone, sandstone and tuff samples were tested under laboratory conditions. It was observed that the abrasiveness of each type of rock saturated with liquid having pH-4 degree was higher than the obtained results from testing the samples saturated with liquids having pH-7.5 and 10 degree. It can be thought that abrasive minerals have come out rapidly because of contacting acidic liquid with the rock surface.

Decrease in point load strength for each type of rock was observed when the rocks were saturated with liquids. Also, there was no meaningful relationship between point load strength and water adsorption of tested rocks.

Although many methods of determining the abrasiveness index of rocks have been proposed in the literature, all the methods are performed by using dry samples of rocks. However, mining operations can be carried out by mining machines exposed to mine water in different properties when the mining conditions are considered. So, rapid tool wear of the machines working such conditions can be anticipated as the abrasiveness of rocks has shown tendency to rise in acidic media.

It is suggested that steel cube test should be further performed on other igneous, metamorphic and sedimentary rocks in order to gain a better understanding of the effect of liquids on the abrasivity of rocks. Also, it would be useful to compare the laboratory obtained steel cube abrasiveness index with the cutter replacement rate of various types of excavating machines.

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