

Effect of Cone Indenter Hardness on Specific Energy of Rock Cutting

Cihan DOĞRUÖZ¹, Naci BÖLÜKBAŞI²

¹Dumlupınar Üniversitesi, Mühendislik Fakültesi, Maden Mühendisliği Bölümü, 43100, Kütahya

²Ortadoğu Teknik Üniversitesi, Mühendislik Fakültesi, Maden Mühendisliği Bölümü, 06660, Ankara

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Abstract: The effects of rock mechanics parameters on performance of various tunneling and excavation machines used in tunneling application has been an important issue in conventional, NATM, and TBM tunneling. Mechanical feature of machine performance is important for cutting specific energy and cutting parameters. Specific Energy (SE) of rock excavation depends on rock features such as uniaxial compressive strength (UCS), Brazilian tensile strength (BTS) and standard cone indenter hardness (Is), as well as bit shape and size, cutterhead design, and cut geometry. In this study, impact of cone indenter hardness on SE has been examined and results of statistical analysis on laboratory data related to linear scale cutting of various rock types with different pick cutters are discussed. The results shows that there is a strong relationship between cone indenter hardness and laboratory specific energy. The cone indenter hardness results are between 0.30 MPa and 3.63 MPa. The tests were applied on weak and moderate rocks types. Based on the test results, two different prediction models were created using second order functional regression analyses.

Kaya Kesmede Koni Delici Sertliğinin Spesifik Enerjiye Olan Etkisi

Anahtar Kelimeler

Mekanik kaya kazısı,
Özgül enerji,
Koni delici sertliği

Özet: Tünelcilik uygulamalarında kullanılan çeşitli kazı makinalarının kaya mekaniksel özelliklerine olan etkileri geleneksel, NATM ve TBM tünelciliği yöntemleri için büyük önem arz etmektedir. Makine performansının mekanik özellikleri, kesme özgül enerjisi ve kesme parametreleri açısından önem arz etmektedir. Kayaç kazısının özgül enerjisi, kesici uçların tasarımlarına, ebatlarına, ve kesme geometrilerine bağlı olduğu kadar tek eksenli basma dayanımı, Brazilian çekme dayanımı ve standart koni delici sertliği gibi kayaç özelliklerine de bağlı olabilmektedir. Bu çalışmada, koni delici sertliğinin özgül enerji üzerine etkisi ve çeşitli kayaç örnekleri için değişik ebatlarda kesici uçlarla yapılan kesme işlemlerinin istatistik modeller kurularak doğrusal kesmede etkileri incelenmiştir. Elde edilen sonuçlara göre, laboratuvar özgül enerjisi ile koni delici sertliği arasında güçlü bir ilişki olduğu gözlemlenmektedir. Yapılan testler sonucunda koni delici sertlikleri 0.30 MPa ile 3.63 MPa arasında değişmektedir. Bu çalışmada zayıf ve orta sertlikte kayaçlar üzerinde deneyler yapılmıştır. Elde edilen sonuçlar kullanılarak ikinci dereceden üssel fonksiyon metodu ile regresyon yöntemi uygulanarak iki farklı tahmin modeli oluşturulmuştur.

1. Introduction

Cutting picks on a roadheader cutterhead become blunt in time and require replacement. It is important to replace the picks when they reach a critical degree of wear at which point considerable increase in cutting forces and specific energy is experienced. Most performance estimate models assume sharp picks for their calculation, whereas in practice wear on the tip develops due to various causes and it

should be processed into account for accurate prediction of machine in the field. The degree of variation in cutting forces and specific energies as a result of pick wear is unknown and rarely studied in sufficient detail to allow for proper adjustment of performance estimation formulas. The impact of tool conditions on mine excavation process depends on the pick conditions and tip geometry, as well as a variety of other parameters, enclosing strength features of rocks, rock abrasivity, size, type of cutting

tools, shape and configuration of cutting picks on the excavating heads. Additional parameters include the specific energy of cutting (MJ/m^3), the cutting forces (kN) available on the excavation machinery. The cutting tools with abrasive wear on rock-pick interaction is important as the initial and product costs and delays experienced for the modification of the worn out parts reflects on machine performance. This paper focuses on the variation of specific energy of cutting as a function of cone indenter hardness (I_s) to predict the production rate of various excavation machine in mining and tunneling operations.

2. Roadheaders

Roadheader machines break rock by using tungsten carbide cutting tools and these machines are also the partial face excavation equipments. An electric motor is operating the cutting head through heavy duty gearbox for milling and ripping type cutting movements [1]. Hydraulic cylinders are controlling the boom action to provide enough force to move the cutting head in the process. The work faces are used for tramming and for that reason the equipment is supporting the machine track. According to Neil et. al, less than 100 MPa compressive strength values in sedimentary rocks are operated by roadheaders [2]. In the joints, bedding planes, fractures and other different structures, some rough rocks can be rarely excavated. Figure 1 shows the typical ripping and milling type roadheaders.

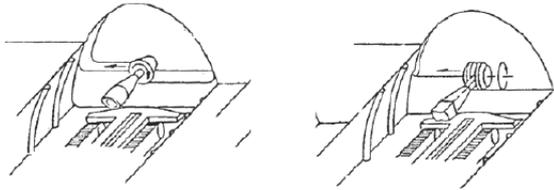


Figure 1. Ripping and milling methods

The roadheaders are categorized as sizes and rock-cutting abilities which are the functions of their weights and installed power [3]. Roadheaders are ranked from small size to 30 tones, midsize between 30-70 tones and large size between 70-120 tones [2]. According to Tucker, roadheaders are labeled as their weight. Light duty roadheaders are weighted up to 30 tones and the cutting capabilities are up to 70 MPa, medium duty roadheaders are weighted between 34-45 tones and capabilities are up to 100 MPa and heavy duty roadheader are weighted between 34-45 tones and the capabilities are up to 120 MPa [4].

Different methods has been proposed for estimation of the machine production rate and the most reliable ones are by Bilgin et al, Copur and Neil [2,5,6]. A simple but reliable method for performance prediction of roadheaders is to use specific energy of cutting [7]. For a given type of rock, cutting tool, and machine, if the specific energy of cutting and installed cutterhead power is carried out, the instantaneous production rate can be figured out as follows:

$$IPR = \frac{HP \cdot \eta}{SE} \quad (1)$$

Where HP is machine power (in kW or hp), η is mechanical efficiency of the system, and SE is the specific energy in $\text{kw-hr}/\text{m}^3$ or $\text{hp-hr}/\text{cyd}$. The resulting instantaneous production rate or IPR is in m^3/hr (cyd/hr). Typical values for SE and η for certain types of machines and rock types can be found in publication by Rostami [7]. With the numbers in this table and given the installed cutterhead power of the machine, one can calculate the related production rates. Production rate in terms of tonnage can be simply calculated by multiplying the excavated volume by specific gravity of the rock. Once the production rate is calculated, the rate of penetration (ROP) of the machine can be calculated as follows:

$$ROP = \frac{IPR}{A} \quad (2)$$

Where A is the sectional area of opening in m^2 (ft^2) and ROP is in m/hr (ft/hr). Obviously, the units used in calculation should be consistent. The advance rate (AR) of the machine which is the daily footage mined in a single heading can also be calculated by:

$$AR = ROP \cdot U \cdot N_s \cdot Hrs \quad (3)$$

Where U is machine utilization in % total time, N_s is number of shifts per day, and Hrs is number of hours per shift. Utilization of the excavation machines are estimated based on the ratio of the time machine is actually excavating rock to the total time per shift or day [8].

3. The Cone Indenter Hardness Test

Cone indenter device was developed by Mining Research and Development Establishment (MRDE) in England [9]. This equipment measures the rock strength without the preparation of shaped and processed samples. According to McFeat Smith, cutting of drag pick tools has been released to be an important indentation behavior and a good relationship occurs between the cone indenter hardness and capacity of selective excavation [9, 10].

Some rock types having low indenter values require high cutting specific energies. For that reason, it is not commonly used for all rock types due to the deviation of the observations [11].

Figure 2 shows the NCB Cone Indenter device developed to carry out the hardness of the rocks by using the methodology of measuring the resistance by tungsten carbide cone material. This instrument includes a steel bench 175 mm long and the strip is pressed along the axis. A dial gauge is used for the measurements and it is existed in such a way that its

bore is in contact with one side of the steel ribbon. The tungsten carbide material with a conical tip which is 40° angle is fitting a micrometer in the mid of the longitudinal side of the equipment. The steel ball cylinder is available to rotate in the bed of the equipment. The micrometer is utilized to find out the amount of indentation. The gauge is used for the indication of the distance of the spring deflection. The actions of the indenter in so many ways is similar to point load index testing unit, which is very popular in both laboratory and field rock mechanic testing to represent rock strength, both UCS and BTS. This similarity and its implications will be discussed later since the availability of cone indenter is very limited, but point load index has been commonly used in rock mechanics testing.



Figure 2. NCB Cone Indenter

Testing procedure is described in the apparatus manual [9]. There are main steps of measuring cone indenter hardness. Test specimens with approximate dimensions of 6x12x12 millimeters should be prepared with sound and clean test surface. The specimen is placed between the platens and cone is moved to hold the sample in place firmly. Dial gauge is set to 0.0 and micrometer reading is taken (M_0). The micrometer is then turned until the dial gauge shows 0.635 (D_1) and the micrometer is read again (M_1).

The penetration of the cone into the specimen is calculated from the formula;

$$P = (M_1 - M_0) \cdot D_1 \quad (4)$$

The standard cone indenter number is calculated by;

$$I_s = 0.635 / P \quad (5)$$

In this study, rock mechanics tests were also applied for twenty different types of sedimentary rocks. The rock are named as limestone, clayey limestone, mudstone, mudstone siltstone, marl, altered tuff, lithic tuff, claystone, siltstone, andesite and travertine. The uniaxial compressive strength ranges vary from 5.75 MPa to 64.15 MPa, Brazilian tensile strength results vary from 0.59 MPa to 10.17 MPa, shore results vary from 3.10 to 46.50 and Schmidt hammer hardness vary from 16.18 to 45.80.

4. Relationship between Cone Indenter Hardness and Specific Energy

Many studies have been carried out to establish relationships between the cutting performances of various machines and the properties of the rock [2,8,12,13]. According to Bilgin, the wide variation of geologic and geotechnical characteristics of the rock formations encountered around Istanbul gave the unique opportunity to correlate, in the past, the rock mass properties with the performance of spiral type or longitudinal roadheaders used to drive the tunnels of Istanbul sewerage project [14]. The laboratory-specific energies were calculated in the study using the following formula which was studied by Balci in the past [15];

$$SE = \frac{Fc}{Q} \quad (6)$$

where SE (MJ/m³) is the laboratory specific energy, Fc (kN) is the cutting or drag force, and Q (m³/km) is the yield per unit length of cut.

The performance of roadheaders has been investigated for various formation types [16]. Ergin and Acaroglu have developed a new computer program to analyze the stability states of roadheaders and the method allows analyses for both longitudinal and transverse cutting head type machines either at one point on the excavation face or whole faces [17]. Ocak and Bilgin have investigated on İstanbul -Kadıkoy metro tunnels which are planned to be constructed in two stages and they have found out the net cutting rates, net braking rates in their studies [18]. Thuro and Plinninger have examined the connection between some geological parameters, cutting performances and bit wears by means of German case studies in different geological settings [19]. Physical and mechanical properties of surrounding rocks and ore zones are examined by investigations found out on samples taken from an underground ore mine by Yetkin and his colleagues [20].



Figure 3. Setup for the rock cutting experiment and the rock sample test

As it can be seen in Figure 3, specific energies were found out by using the linear cutting setup system in mine mechanization laboratory of mining engineering department at Middle East Technical University. The equipment of dynamometer, cutting pick and recording unit are utilized to make linear cutting and carry out the cutting forces. The method uses the chisel type cutter picks made up of tungsten carbide with %10 cobalt material.

Figure 4 indicates the relationships between the laboratory cutting specific energy measured in full scale cutting tests by various picks and standard cone indenter hardness at different wear flats [21]. It can be observed that the relationship is linear and rather high correlation exists between the SE and the I_s values. The rate of increase in SE versus I_s is higher with larger wear flats on the picks. For example measured SE on a cutting tool with 4 mm wear flat is about 3-4 times higher than SE for sharp picks when cutting a given rock with the same cone indenter hardness. This indicates the sensitivity of the SE to tool wear.

If a limit in specific energy can be considered to show poor cutting performance, this limit can be used to indicate the preferred amount of wear on tools before changing to maintain a reasonable machine performance. For example if SE of 25 MJ/m³ is used for certain rock type or machine power to achieve a minimum rate of production and to meet certain project production and advance rate targets, then the critical wear flats for changing the tools can be selected as a function of different rock types as represented by cone indenter numbers. One should keep in mind that the critical value of SE for various rock types is different since stronger rocks typically require more forces and energy to cut. Similarly, one should also be cognizant of the fact that in hard abrasive rocks blunt tools with large carbide is used to increase the cutter life. Thus in hard abrasive rocks this analysis can be revisited to account for the fact that in most mechanical excavation operations efficiency and SE is sacrificed hard rock for longer cutter life which means lower downtime for bit change and to avoid frequent machine stoppage for bit change and thus low utilization rate. As an example, Figure 5 shows that it is possible to maintain SE below 25 MJ/m³ with 4 mm wear flat for rocks having cone indenter number of less than 1.2.

As noted, above, due to the specific limits of the study and use of wedge shape cutters, these limits and in particular the SE values shown in these Figures are not directly applicable for use in predicting performance of roadheaders due to the variation in cutting tools and machine specification. However, this analysis indicates that a small and limited study can help the operators to develop a better plan for pick change to optimize their operation relative to production rate and utilization.

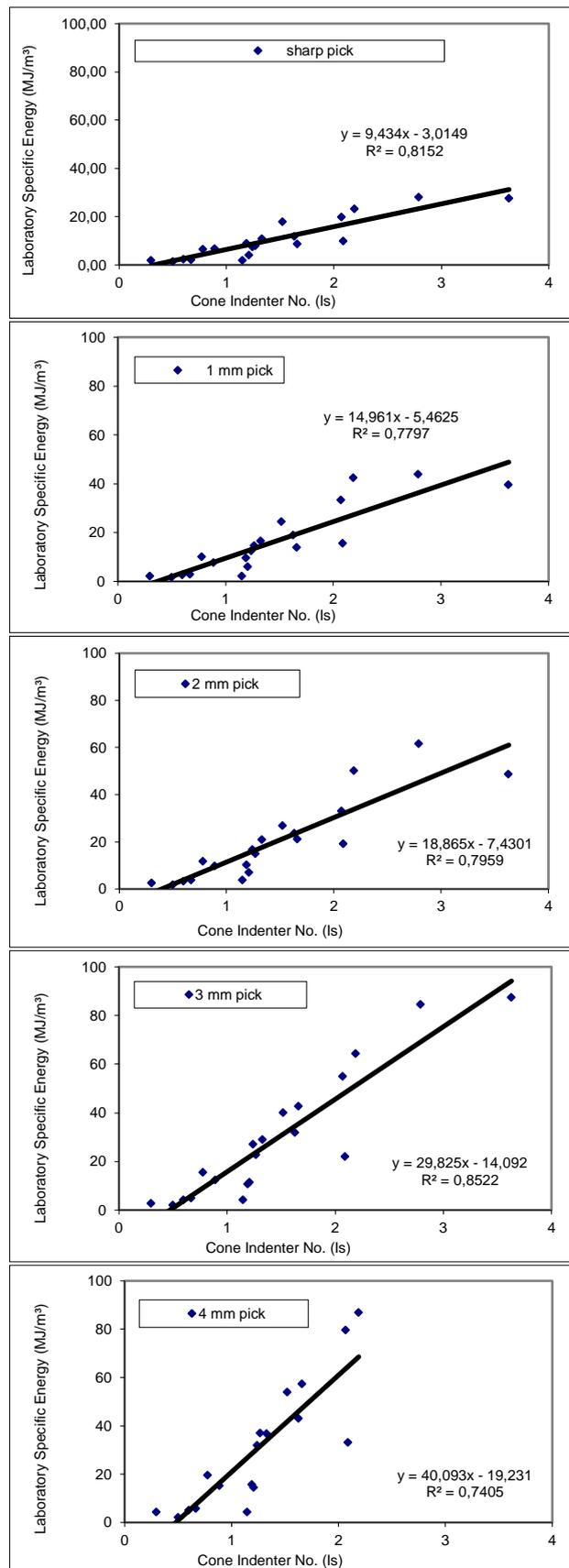


Figure 4. Relationships Between Cone Indenter Number and Laboratory Specific Cutting Energy at Different Wear Flats

If the relationships between the cutting forces and I_s is examined, it is identical to what was discussed since the cutting or drag force was used for

estimation of SE in the laboratory testing. Thus the drag forces or cutterhead torque is anticipated to increase 2-3 times with 3-4 mm wear flats as compared to sharp picks for rocks with higher cone indenter hardness values.

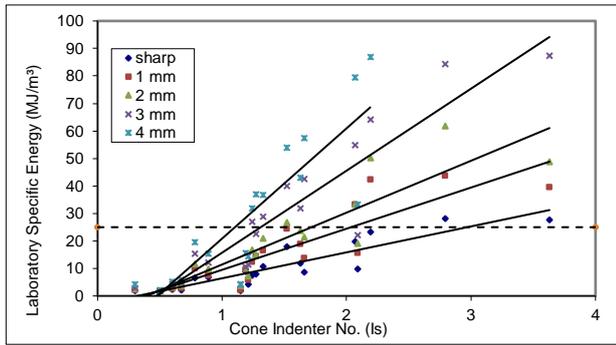


Figure 5. Critical Wear Flats for Varying Standard Cone Indenter Numbers

5. Statistical Analysis of the Results

The statistical analyses is utilized to create the best fitted model for the regression analyses. Although the first order of the models are common, the second order models are reliable and convenient. While the experimenter is relatively close to the optimum, a model that incorporates curvature is usually required to approximate the response. In most cases, the second-order model is adequate [22].

The experimental data in the testing program was used to seek relationships between SE and various cutting and rock mechanics parameters. In this study, regression models were obtained to estimate SE based on UCS, BTS, I_s , and wear flat. Two regression models with highest coefficient of correlation are as follows;

$$SE_L = -3.352W_F - 0.043UCS^2 + 0.065SH^2 + 6.867W_F * I_s + 1.571UCS * I_s + 0.046UCS * SH - 2.506I_s * SH \quad (R^2=0.904) \quad (7)$$

$$SE_L = -2.795 W_F + 23.075 BTS - 61.530 I_s + 6.765 W_F * I_s + 34.400 I_s * D \quad (R^2=0.895) \quad (8)$$

where SE_L is laboratory specific energy (MJ/m^3), W_F is wear flat (mm), UCS is uniaxial compressive strength (MPa), I_s is standard cone indenter number (MPa), SH is Shore hardness, and D is density (g/cm^3).

Using analyse of variance methodology, f test and t test were applied and the results were modelled as it can be seen in Figure 6. The correlation coefficients show us, there is rather good relationship between the dependent and independent parameters in the models.

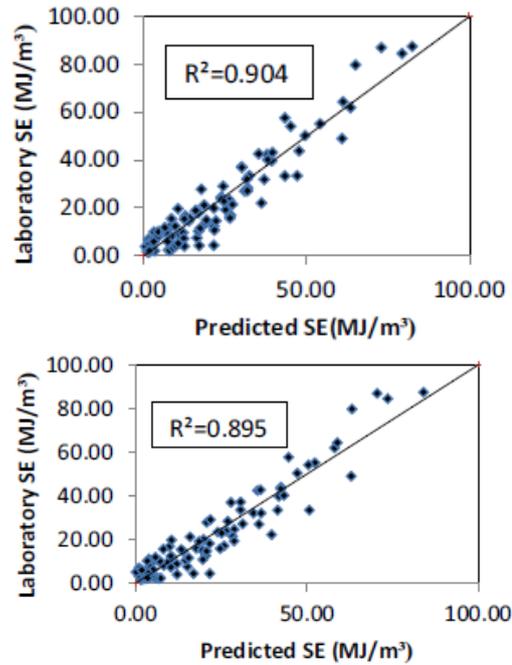


Figure 6. Comparison of laboratory specific energies and predicted values for two models

6. Conclusion

In this study, effect of tool wear and rock properties represented by cone indenter hardness on laboratory cutting specific energies have been studied. The results show good correlation between the specific energy, amount of tool wear, and the cone indenter hardness. Both specific energy and cutting force increase rapidly with increasing cone indenter hardness and wear of the tool. Specific energy and cutting force increase about 3-4 times with 4 mm wear flat as contrasted to sharp pick in the same rock sample. If a certain SE value is used as a measure of rock cutting efficiency to meet certain production goals, the acceptable limit of wear flat for a given pick type can be estimated and communicated with operators to optimize the productivity of the unit. This can be done based on limited testing in selected rock type and tools with known amount of wear to allow for estimation of Specific energy (in the field or in the lab) and quick statistical analysis of SE as a function of cone indenter hardness, or perhaps UCS and BTS.

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