COMPARISON OF SMALL SCALE AND FULL SCALE ROCK CUTTING TESTS TO SELECT MECHANIZED EXCAVATION MACHINES

SUMMARY

The specific energy criterion is a simple method for a quick and informative performance prediction of all types of mechanical excavators. This criterion uses machine installed head power, total system efficiency and the specific energy required for cutting a particular rock type with a certain type of tool. Using the specific energy concept, achievable production rates are calculated for a machine with a known power available on the cutterhead. Specific energy is defined as the amount of energy required to break a unit volume or weight of rock expressed in kWh/m$^3$ or MJ/m$^3$. This value can be determined from small-scale or full-scale laboratory linear rock cutting experiments at different cut spacings and depths. For this purpose in this work small-scale and full-scale (Linear cutting machines) rock cutting experiments were performed on rock samples obtained from 18 different types of rocks. Cutter forces acting on a cutter in three directions (the cutting force, the normal force, and the sideway force) and, specific energy values were measured during testing. In addition, physical and mechanical property testing were carried out and relationships between specific energy values and rock mechanical properties were analyzed using the method of least squares regression analysis.

In chapter 2, extensive literature review was performed about the research studies conducted over the years on performance prediction models for mechanized cutting systems. There are several models for performance prediction of roadheaders, each one based on some theories and experiences. The theoretical models are based on the analysis of the forces or the energy required to excavate a unit volume of rock and to relate that to the rock properties such as rock uniaxial, tensile, and shear strength, geological features of the ground such as RQD, and finally available power or thrust on the machine. A number of methods have been developed to estimate penetration rate of mechanical excavators and their efficiency in different rocks type. The methods typically correlate the penetration rate to particular parameters such as unconfined compressive strength (Graham, P.C., 1976), total hardness (Tarkoy), full-scale linear cutting test (L. Ozdemir, 1997), small-scale core cutting test (McFeat Smith, Fowell, R.J., 1977), rocks joints, fissures, compressive strength and abrasivity (Aleman, V.P., 1983), rock mass index, compressive strength and ground water (Sandbak, L. A., 1985), petrographic properties of rock, compressive strength and Schimazek abrasivity (Gehring, K.H., 1989), Rock Impact Hardness Index (Matsui, K., Shimada, H., 1993) etc. The overall study of the literature survey on performance and efficiency of the mechanical excavators show that this scientific area needs extensive further studies.

Among in these methods full-scale linear cutting test and small-scale core cutting test are the most widely used and accepted to estimate production and advance rate and efficiency of mechanical excavators. The full-scale linear cutting test is more expensive and complex than the small-scale core cutting test and requires up to 1 m x
m x 0.6 m rock blocks in size. Sometimes it is impossible to get that big rock samples during the geotechnical exploration studies. However, core samples can easily be obtained during geotechnical investigations. To get specific energy by using small-scale rock cutting tests on core samples is easy and less expensive method than the full scale rock cutting tests.

In chapter 3, data acquisition system of the small-scale rock cutting machine was presented. Small-scale test machine was not ready and needed a tri-axial dynamometer, data acquisition systems and data analyzing software program. For that reason, old data acquisition system and tri-axial load cell were modified to measure high capacity cutting forces. The main modification to the small-scale rock cutting machine was the putting a strain-gage technology of the tri-axial dynamometer that resolves the cutter into three component forces. The old tri-axial force dynamometer was used for that purpose. The electrical resistance strain gauges were used Measurements group type CEA-06-125 of 6 mm. gauge length with a resistance of 350 ohms and gauge factor of 2.1. The centers of the strain gauges were located on the centre lines of the force dynamometer’s beams and 10 mm. from the ends of the measuring beams. The adhesive used was M-Bond 200 type which is a rapid curing cyanoacrylate.

The tri-axial force dynamometer should have ability to measure the three forces (normal, cutting, sideway forces) without interaction, i.e. each component of force, should not influence the indicated values of the other measured components. In accordance with standard test procedure, the small-scale rock cutting machine’s load cell was calibrated by using a hydraulic jack and a steel ball. This process repeated many times to get best correlation during calibration. Calibration loads were varied from 0 to 1650 kgf at 100-kgf increments of jack pressure, and the load cell voltage output was recorded. The dynamometer sends signals via an amplifier to a computer from which loads experienced during a calibration were obtained. Data were then used to perform linear regression analysis of voltage vs. loads. From this analysis, the slope and intercept values were obtained to convert voltage to force. This was done separately for the normal, rolling, and side force components. An Excel macro was used to reduce the data obtained from the regression analysis.

In chapter 4, the rock physical property testing including UCS, (Uniaxial compressive strength; the single most common and useful test for determining rock strength), BTS, (Indirect (Brazilian) tensile strength; when combined with UCS, an excellent measure of cuttability), elastic and dynamic constants (E, v), Schmidt hammer (N-24 and L-9 types) tests, and density for different rock types (Sandstone, Mudstone, Shale, several Volcanic Rocks, Chromites, Trona, and Copper) were performed under strict quality control guidelines and in full-compliance with ASTM and/or ISRM established test procedures.

In chapter 5, laboratory specific energy values were obtained using the results of small-scale and full scale linear cutting tests. Specific energy values were calculated according to following equation: \((\text{Mean drag or rolling force} \times \text{length of cut})/(\text{weight of excavated material} \times \text{rock density})\). During rock cutting experiments at least three cuts were performed at each of the penetrations and spacings used and the mean value of specific energy obtained. An extensive database of rock cutting tests results was created in order to carry out statistical analysis. The size distribution of the muck collected from small scale rock cutting experiments for relieved and unrelieved
test conditions was determined through sieve analysis. Coarseness index (C.I.), a non-dimensional number, gives a measure of the size and distribution of debris from the excavated cut. This is calculated by sizing the rock chip and dust sample in a standard set of sieves and determining the sum of the cumulative mass percentages of each size. CI number for each cut was calculated and correlated with the optimum specific energy values. The results show that there is a strong relationship between the coarseness index of muck from an optimum spacing of rock cutting test and the specific energy.

Following is a description of the small-scale and full-scale rock cutting testing equipments. In addition, the steps involved in sample preparation, surface conditioning, and the test procedures are discussed in this chapter.

- Small scale cutting test

This test has been developed by McFeat Smith and Fowell to simulate the cutting action of drag-pick tools and to measure the corresponding cutting properties of rock materials. It is suggested a standard laboratory rock cutting test by international rock mechanic commission to measure the cuttability of rocks. In this test a core of 7.6 cm. in diameter or a small rock sample of 20 x 10 x 10 cm is fixed in a table of a shaping machine and cut by a chisel pick having a rake angle of –5 degrees, a clearance angle of 5 degrees, tool width of 12.7 cm and a cutting depth of 5 mm. as a standard conditions. The tool forces in three orthogonal directions are recorded using a force dynamometer and the specific energy in MJ/m³ or kWh/m³ is calculated by dividing the mean cutting force FC by the yield Q (the volume of rock or mineral obtained by unit distance of cut). The test results, which may be classified as index values, are evaluated according to previously accumulated field performance data.

- Full-scale cutting test

This method is the most realistic approach, since a block of 70 x 50 x 50 cm. in size is cut in the laboratory with an actual size cutter (point attack tool, chisel picks etc.). All the full-scale rock cutting tests were carried out with an S-35/80H conical cutter manufactured by Sandvik. The full scale linear cutting machine features a large stiff reaction frame on which the cutter is mounted. A triaxial load cell, between the cutter and the frame, monitors forces. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. All the full-scale rock cutting tests were carried out with clearance angle 170°, attack angle 55-560°, cutting speed 12.7 cm/sn and data recording rate 2000 Hz constantly of conical cutter.

Full-scale testing minimizes the uncertainties of scaling and any unusual rock cutting behavior not reflected in its physical properties. The force data is used as input for selection and design of an excavator, selection of cutter, definition of optimum cutting geometry and prediction of performance and cost. The cutting force, normal force, sideways force and specific energy values are obtained with different depth of cut and tool spacing and the production rate of a given mechanical excavator is calculated by the following formula:

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ICR = 0.8 \frac{P}{SE}
\]  

(1)
In this formula ICR is instantaneous production rate in m$^3$/h, P is cutting power of the mechanical excavator in kW and SE is optimum specific energy in kWh/m$^3$.

Chapter 6 contains the development of new formulas for specific energy values estimation. The statistical model equations were developed based on the regression analysis. Since specific energy values are affected by several factors which are especially rock properties and cutting tools, not only are simple regression also multiple curvilinear regressions analysis applied together to see the difference. To find the reliable relationship between cutting results and rock properties, specific energy and all rock physical properties data carried out using some statistical softwares. These formulas were validated by comparing the results with the measured specific energy values in the small-scale and full-scale laboratory cutting tests. The selection criteria for the best model are:

- Coefficient of multiple determination ($R^2$)
- t-test
- F-test

Dependent and independent variables are described to find relationships using regression analysis. The density, uniaxial and tensile rock strength, static and dynamic elastic values, seismic waves, Schmidt hammer values of the rocks and, specific energy values obtained from small-scale rock cutting tests at 5 and 9 mm. depth of cut are chosen as independent variables. SE2 (Specific energy values obtained from optimum s/d using full-scale linear rock cutting test) and SE4 (Specific energy values obtained from unrelieved rock cutting tests using full-scale linear cutting test) are chosen as dependent variables. In addition, the relationship between two different specific energy values obtained from full scale and small-scale rock cutting tests was investigated by using statistical analysis.

Chapter 7 summarizes the results of the thesis work and lists the conclusions. A newly developed specific energy equations with respect to influencing rock property parameters were discussed. The results of the initial analysis showed a very strong and dominant relationship between the specific energy values, rock properties, and the muck size distribution. The unconfined compressive strength, the tensile strength, and Schmidt hammer values are found to have a much more impact on specific energy.

This thesis study primarily intended to focus on development of new formulas for estimating the specific energy from rock properties and small scale rock cutting test for selection of rock mechanical excavators used in tunnelling and mining works. Using specific energy criterion production and advance rates can be estimated for mechanical hard rock excavators. The experimental studies and analysis in this thesis work do not include the effects of some particular rock features such as fabric, grain size and grain shape, abrasiveness, fracture toughness, hardness, and foliation, even though they are known to have some influence on the cutting forces and machine performance.

Consequently, statistical analyses showed that specific energy values can be predicted from rock mechanical properties to select most efficient mechanical excavators.