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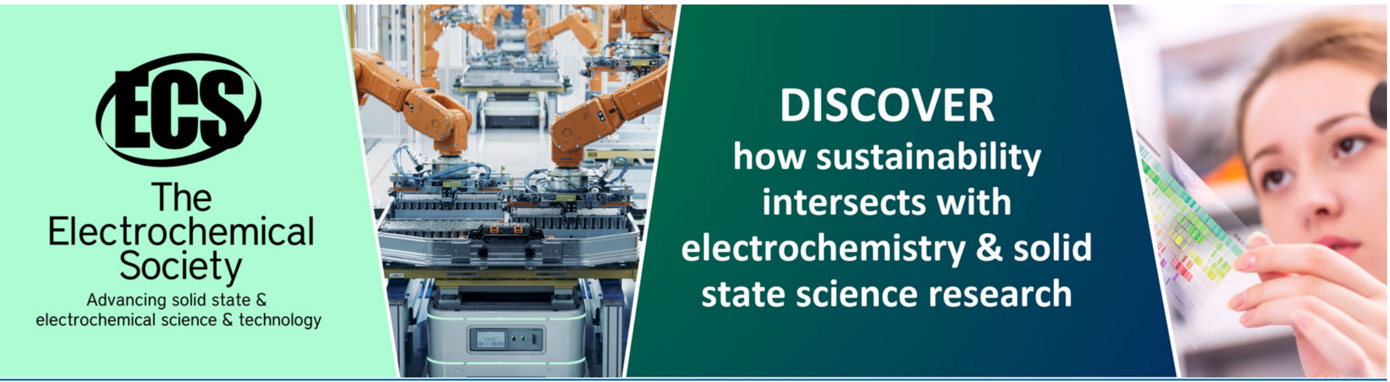

Core Cutting Test with Vertical Rock Cutting Rig (VRCR)

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Abstract. Roadheaders are frequently used machines in mining and tunnelling, and performance prediction of roadheaders is important for project economics and stability. Several methods were proposed so far for this purpose and, rock cutting tests are the best choice. Rock cutting tests are generally divided into two groups which are namely, full scale rock cutting tests and small scale rock cutting tests. These two tests have some superiorities and deficiencies over themselves. However, in many cases, where rock sampling becomes problematic, small scale rock cutting test (core cutting test) is preferred for performance prediction, since small block samples and core samples can be conducted to rock cutting testing. Common problem for rock cutting tests are that they can be found in very limited research centres. In this study, a new mobile rock cutting testing equipment, vertical rock cutting rig (VRCR) was introduced. Standard testing procedure was conducted on seven rock samples which were the part of a former study on cutting rocks with another small scale rock cutting test. Results showed that core cutting test can be realized successfully with VRCR with the validation of paired samples t-test.

1. Introduction

Rock cutting machines are being widely used in both mining and tunnelling applications for approximately 60 years and the demand for these machines is increasing day by day because of environmental issues and market economy since these machines offer higher production rates with safer working environment. These machines can be grouped as full-face and partial-face machines roughly. In mining applications, partial-face machines are being utilized. They include roadheaders, continuous miners, shearer loaders, and ploughs etc.

Roadheaders are very versatile examples of excavation machines since they are mobile and cheaper to purchase when compared with full face tunnel boring machines. Prior knowledge of performance of any mechanical excavator has a key role on project economics and stability since contractors need to know the project duration or production rate in mining or tunnelling operations. Empirical methods, rock cutting tests and theoretical models are the basic tools for performance prediction of excavation machines. Performance of rock cutting machines are defined with instantaneous cutting rate (ICR), tool consumption rate (TCR) and, machine utilization time (MUT). Aforementioned performance prediction methods are related with the prediction of ICR. Among these models, rock cutting tests are the best choice for this purpose [1], since they simulate the cutting action of rock cutting machine in laboratory successfully. However, this laboratory equipment can be found in very limited research centres. Based upon this issue, researchers tried to produce alternative cutting testing equipment to simulate the action of rock cutting machine.

In this study, newly developed mobile rock cutting testing equipment [2-3], vertical rock cutting rig (VRCR), was used to simulate the core cutting test which was developed by Roxborough and Philips [4]. Seven rock and ore samples which were part of a former study were subjected to core cutting test. Results from VRCR for core cutting test were compared with another experimental setup for core cutting test. After calibration with another testing and measurement system, 3 volcanic rock samples were cut with VRCR and a potential performance prediction for these rocks were realized with this method.

2. Rock cutting tests

Rock cutting tests were started to be used in 1950's for a better understanding of cutting mechanism of rocks under the action of picks [5]. Several types of these tests were designed and produced so far. However, we may group these tests as full-scale rock cutting tests and small-scale rock cutting tests.

Full-scale rock cutting tests are employed with real-life cutting tools and they are used to excavate huge rock blocks up to 1 m^3 of volume. All types of cutting tools can be used including drag picks and roller picks. Three-dimensional tool forces with three orthogonal components are recorded during the cutting tests. These components are cutting force (FC), normal force (FN) and, sideway force (FS). These force components are seen in Figure 1.

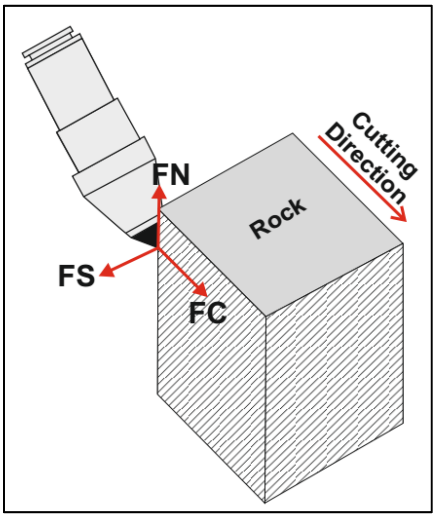

Figure 1. Three-dimensional forces acting on cutting tool

Mean cutting force, which is the average of the all recorded cutting force data in a cutting trial is used to calculate the specific energy which is the best indicator of cutting efficiency with the equation given below.

$$SE = \frac{FC}{Q} \quad (1)$$

where SE is the specific energy (MJ/m^3), FC is the mean cutting force (kN) and, Q is the yield occurred in unit cutting length (m^3/km). Picks located on the cutting head are placed with a special array to interact themselves when cutting rocks. In laboratory cutting tests with full-scale testing equipment, relieved cutting tests are also realized to simulate the field cutting conditions and, also to find the optimum specific energy to be used in performance prediction. Relieved and unrelieved cutting conditions are seen in Figure 2.

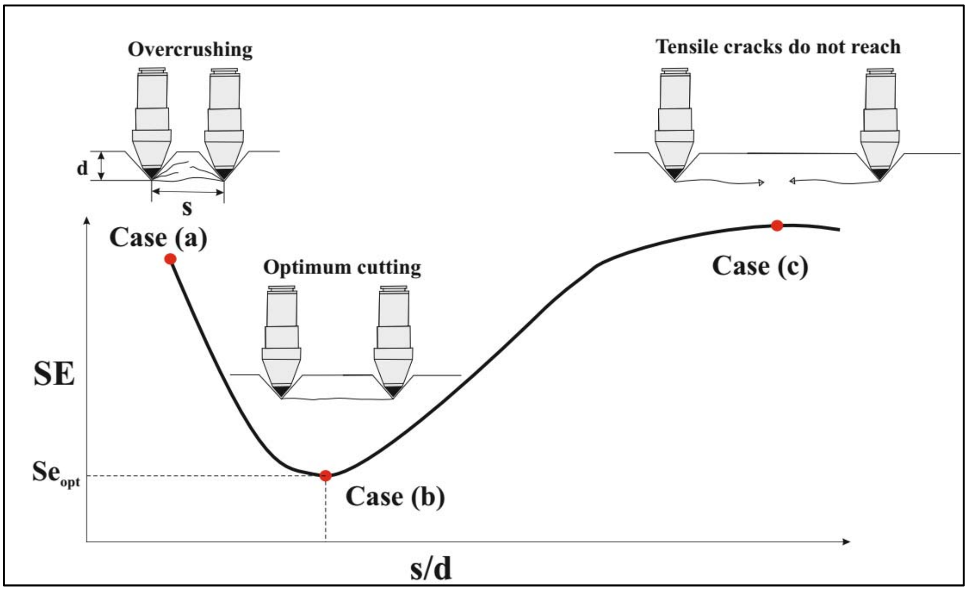

Figure 2. Effect of ratio of tool spacing to cutting depth on specific energy

Case (a) and (b) represents the relieved cutting condition and case (c) represents the unrelieved cutting. In case (a), picks are very close to each other and overcrushing and inefficient cutting occurs. In case (b), cutting is the most efficient one and this point is regarded as optimum cutting configuration and the specific energy in this point is regarded as optimum specific energy (SE_{opt}). This value can be used to predict the ICR of any mechanical miner with using the equation below [6].

$$ICR = k \frac{P}{SE_{opt}} \tag{2}$$

where ICR is the instantaneous cutting rate (m^3/h), P is the cutting power of the machine (kW), k is the energy transfer ratio (0.45-0.90), and SE_{opt} is the optimum specific energy (kWh/m^3). Despite to the superiorities of full-scale testing equipment, they have some drawbacks such as they can be found in very limited research centers and they require very experienced crew and huge rock blocks. Also, these tests are very hard to be performed. Due to these issues, several researchers tried to develop alternative small-scale stationary or mobile rock cutting testing arrangements [4,7-9]. Among these, the most used and reproduced one is the equipment of Roxborough and Philips [4]. This testing arrangement is called small-scale rock cutting test or core cutting test. McFeat-Smith and Fowell [10] suggested a standard method for cutting cored rock samples having 76 mm of diameter. Cutting conditions of this method is given in Figure 3.

McFeat-Smith and Fowell [10] used this suggested method to classify the rocks according to roadheader excavation with using a table and a graph. They found an inverse trend between core cutting test specific energy with ICR of some roadheaders. Also, some other researchers found similar trends which were given in Figure 4. With this graph, one may find the cutting rate of a roadheader with similar properties with roadheaders given in this graph.

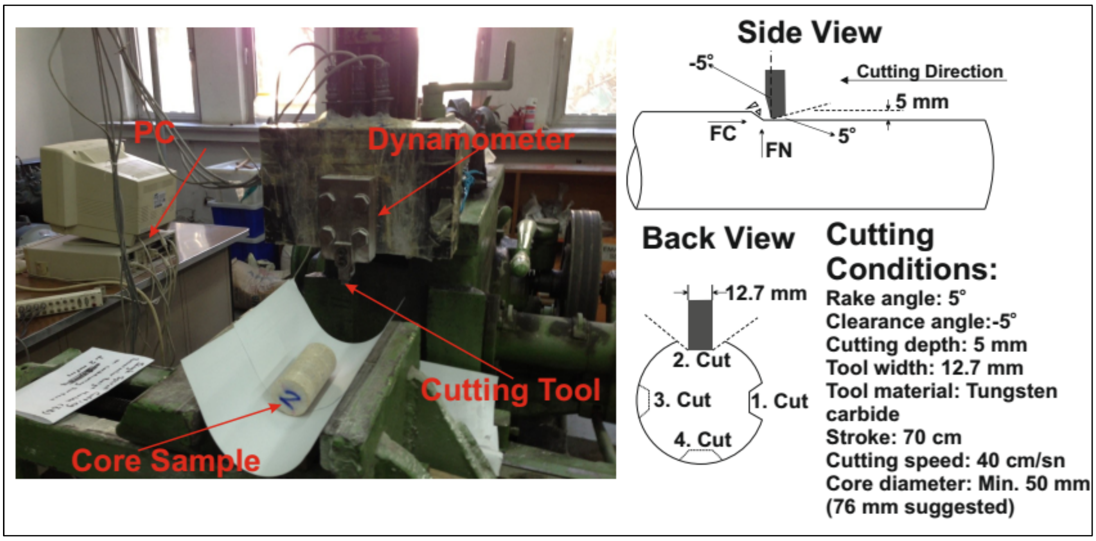

Figure 3. Core cutting testing arrangement in Istanbul Technical University and testing conditions [2].

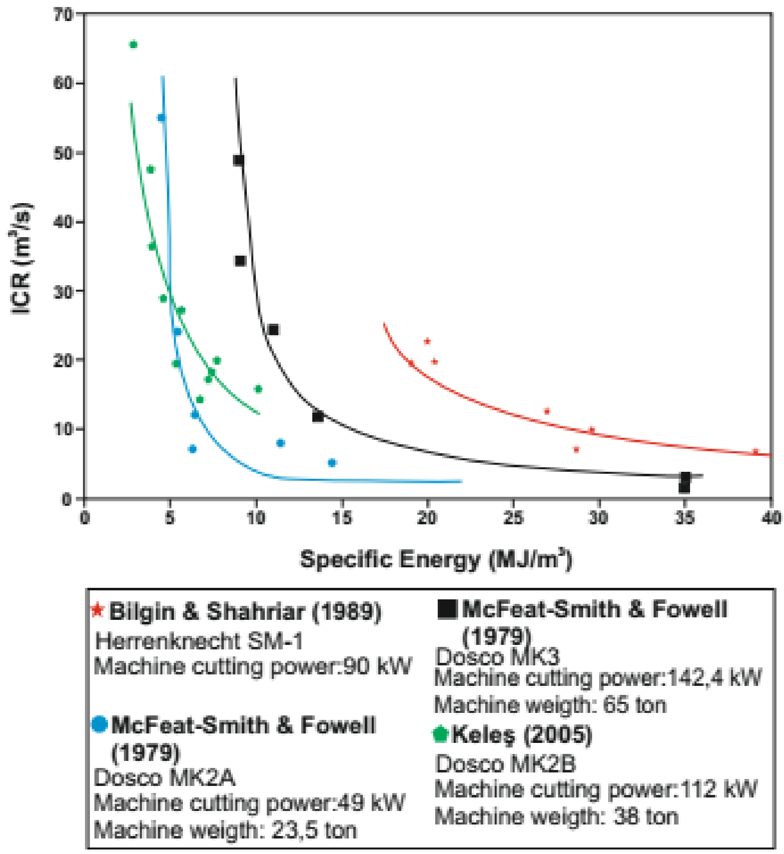

Figure 4. Plots for prediction of ICR from SE suggested by different authors [2, 10-12].

Core cutting test requires small block or core samples with varying diameters where this kind of small samples are easy to be obtained in comparison with full-scale testing. These tests are utilized with index cutters instead of real-life cutters where sometimes this situation is criticized. However, Bamford [13] stated that this index cutters successfully mimic the action of a real-life cutter.

Core cutting test was stated as an accepted testing method for rock cuttability assessment in a workshop by International Society for Rock Mechanics [14]. In this workshop, mandatory features of a cutting test were stated as below:

- Tests for cuttability ought to be delicate over the whole range of rocks which are within the range for excavation with relevant rock cutting machine,
- Testing should be reliable,
- Testing configuration should be easy, quick and, cheap to be performed,
- Testing configuration should be easy to be reproduced accurately by different
- researchers,
- Testing configuration should require small volume of rock samples.

Despite to some advantages of core cutting test over full-scale rock cutting test, these tests also suffer from some deficiencies. These deficiencies include using an index cutter and small rock blocks, being in very limited research centers as full-scale tests. Also, this method lost the ICR prediction ability to some extent since roadheaders are being produced in wide range of specifications such as cutting power and weight. To overcome this deficiency, Balci and Bilgin [15] correlated the SE_{opt} from full-scale rock cutting test with SE from core cutting test and suggested the plot below.

$$SE_{opt} = 0.60\ SE + 0.68 \quad (3)$$

where SE_{opt} is the optimum specific energy (MJ/m^3) and SE is the specific energy from core cutting test (MJ/m^3).

3. Vertical rock cutting rig (VRCR)

Vertical rock cutting rig (VRCR), developed by Yasar [2], is a fully mountable/demountable mobile testing equipment which can be fit into hydraulic press machines and these machines can be found in almost every rock mechanics laboratory and details of VRCR may be seen in Yasar and Yilmaz [3]. Specifically, a bending press machine was used for execution of the study. Components of testing with VRCR is given in Figure 5. Servo-electromechanical system of the bending machine is controlled by the commercial program on computer. As the piston of the frame travels downwards, piston of VRCR travels in same direction and penetrate into the rock sample by the cutting tool brazed on the tool holder which is clamped below the piston of VRCR. Piston of VRCR is connected to load cell of bending machine. Cutting tool below the piston of VRCR cut the rock and the cutting force data is recorded by the commercial program. Recorded cutting force data are then processed and specific energy is found with using Eq.1.

VRCR is produced to act like a rigid body with a steel having over 200 GPa elasticity modulus. VRCR has eight clamping screws for stabling the rock samples. Core samples of any diameter and block samples up to 10 cm x 20 cm x 23 cm may be conducted to cutting test.

4. Simulation of the core cutting test

In a former study [16], some rocks and ores obtained from Eastern Black Sea Region were conducted to core cutting test in the testing arrangement seen in Figure 3. These samples include dolomitic limestone, travertine, granodiorite, fossilized sandstone, lithic tuff, copper ore and, vitric tuff. Cutting tests were carried out with the suggested method of McFeat-Smith and Fowell [10] on 54 mm core samples with natural moisture content. Mean cutting force values for these rocks were recorded and specific energy values were found. Cutting tests for each rock were replicated at least 2-3 times.

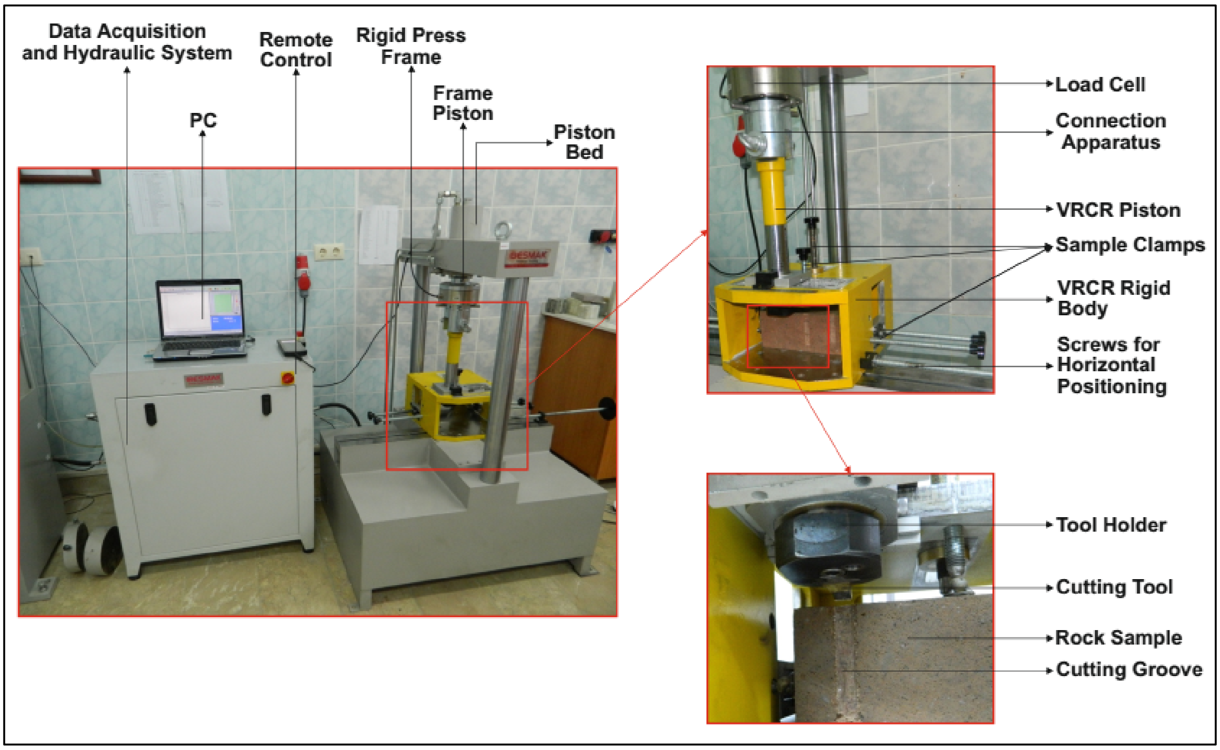

Figure 5. Components of testing with VRCR [3].

Core samples from same rock were preserved until execution of this study. Each test was replicated at least for 3 times for each rock. Core cutting test with VRCR is seen in Figure 6.

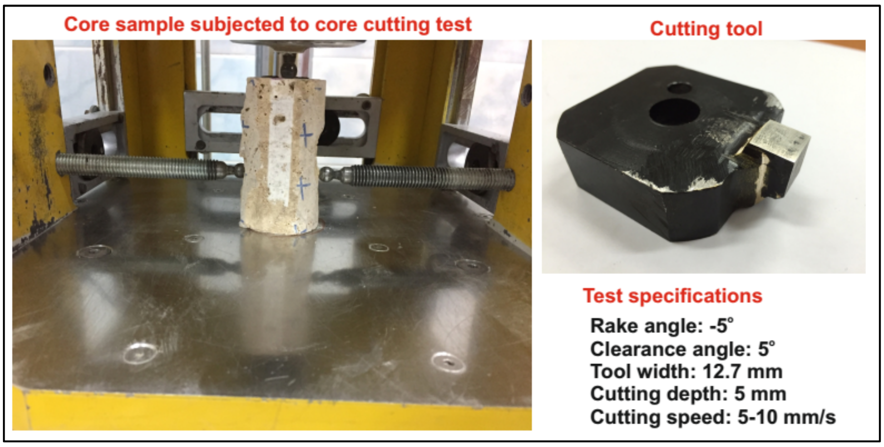

Figure 6. Core cutting test with VRCR

5. Core cutting test on selected rock samples

After validation of the core cutting test with VRCR, some selected rock samples were conducted to core cutting test. These samples include grey andesite, red andesite and, yellow vitric tuff. These rocks selected because of being medium strength rocks, being homogenous and free from visible discontinuities. Uniaxial compressive strength values of these rocks are 99.92 MPa, 72.85 MPa and, 62.48 MPa for grey andesite, red andesite and, yellow vitric tuff respectively. Since Balci and Bilgin [15] used block samples on their study, we used also block samples to determine the core cutting test specific energy and so to determine the optimum specific energy using the Eq. (3). Results of the cutting tests with VRCR is given in Table 2.

Table 1. Results of this study and former study [3, 16]

Rock Sample	d (mm)	SE (MJ/m^3) (VRCR)	SE (MJ/m^3) (Former)	FC/d (N/mm) (VRCR)	FC/d (N/mm) (Former)
Dolomitic Limestone	5	42.21	37.27	688.27	740.76
Travertine	5	23.25	32.72	375.28	483.29
Granodiorite	5	78.03	58.44	979.08	736.70
Fossilized Sandstone	5	50.77	42.85	840.12	921.04
Lithic Tuff	5	24.45	28.56	318.62	447.30
Copper Ore	5	38.79	43.70	775.84	1127.81
Vitric Tuff	5	15.96	18.03	243.22	312.84

Table 2. Results of core cutting test

Rock Sample	d (mm)	Q (m^3/km)	SE (MJ/m^3)	FC (N)	SE_{opt} (MJ/m^3) (Eq.3)
Grey andesite	5	0.104	34.10	3493.36	21,14
Red andesite	5	0.100	15.58	1554.33	10.03
Yellow vitric tuff	5	0.105	11.48	1206.78	7.57

6. Discussion of results

Plot of the results of this study and the former study [16] is given in Figure 7. Figure 7 shows the plot of this study versus former study. It is clearly seen that the SE values found from both experimental arrangements aggregated near the 1:1 line and determination coefficient of the plot is as high as 0.89.

Figure 7, also, shows the plot of this study versus former study. It is clearly seen that the mean cutting force values found from both experimental arrangements aggregated near the 1:1 line and determination coefficient of the plot is as high as 0.67.

These results showed that the mean cutting force and specific energy values, which are found with using VRCR, are significant. Force data was validated with an external load cell which is not mentioned for not giving the redundant details. Also, delicacy of the measuring system to other experimental variables, such as cutting depth and rock strength, were validated in previous studies [2,3].

After validation of the testing with VRCR, practical usage of the core cutting test is realized with performing a possible performance prediction of a raodheader with the results of core cutting test. Performance prediction with the curves suggested by McFeat-Smith and Fowell [10] or other researchers has a limited prediction ability. For an instance, in performance prediction of an imaginary roadheader application in selected 3 rocks with Figure 4, only curve of Dosco MK3 prediction curve is the only choice since, obtained specific energy values are met only with this line. So, if we wish to predict the performance of Dosco MK3 in massive formation of these 3 rocks using Figure 4, ICR of this machine will be 3.28 m^3/h, 9.7 m^3/h and, 18.9 m^3/h for grey andesite, red andesite and, yellow vitric tuff respectively.

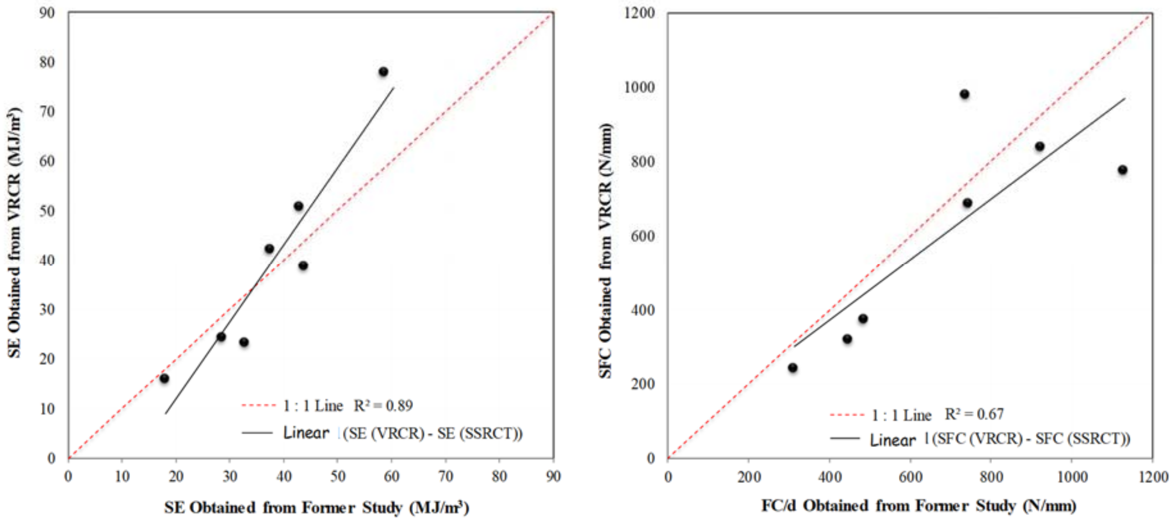

Figure 7. Plot of SE and FC obtained from VRCR and former study [3]

On the other hand, if we opt the predict the ICR of this machine with using Eq. (2), we should utilize the SE_{opt} obtained from Eq. (3). k value for the Dosco MK3 is selected as 0.40 with the recommendation of Bilgin et al. [17] for being an axial head roadheader. ICR of this machine is found as 9.7 m^3/h, 19.92 m^3/h and, 27.12 m^3/h for grey andesite, red andesite and, yellow vitric tuff respectively.

ICR values predicted with Figure 4 seems to be lower than Eq. (2) for all of the rocks. Eq. (2) is a more flexible model than reference curves. It takes the machine-rock (k) and tool-rock interaction (SE_{opt}) into account which makes this model more powerful than the other model. So, these values obtained by Eq. (2) seems more reasonable. However, it should be kept in that these ICR values are calculated for massive formations. ICR values for formation containing discontinuities should be evaluated separately.

Rock cutting testing with VRCR should be investigated by means of the required features stated by ISRM [14]. It was reviewed in Yasar and Yilmaz [3] and this experiment system satisfied all the requirements listed in previous sections.

7. Conclusions

A previously developed new rock cutting testing arrangement, vertical rock cutting rig (VRCR) was briefly introduced in this study by means of core cutting test. Since VRCR is a mobile and a reproducible testing arrangement, application of core cutting test became as a routine strength test.

In this paper, validation of the testing data from VRCR was accomplished with another core cutting testing arrangement. Additionally, three igneous rock samples were conducted to core cutting test with VRCR. Performance of an imaginary roadheader were estimated with rock cutting tests and with using two methods. It has been seen that performance prediction with using the suggested plot [15] and results of core cutting test was more realistic. Furthermore, it should be concluded that VRCR satisfies all requirements which were stated by ISRM.

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References

[1] N. Bilgin, H. Copur, and C. Balci, "Mechanical excavation in mining and civil industries," *CRC Press*, 2014.
[2] S. Yasar, "Development of vertical rock cutting rig for rock cuttability assessment (in Turkish)," Unpublished PhD Thesis, Karadeniz Technical University, 2017.
[3] S. Yasar , and A. O. Yilmaz, "A novel mobile testing equipment for rock cuttability assessment: vertical rock cutting rig (VRCR)," *Rock Mechanics Rock Engineering* , vol. 50, pp. 857-869, 2017.
[4] F.F. Roxborough , and H. R. Philips, "Experimental studies on the excavation of rocks using picks," *In: Advances in rock mechanics, Proceedings of the Third ISRM Congress*, Denver, pp 1407– 1412, 1974.
[5] M.P. Evenden , and J.S. Edwards, "Cutting theory and coal seam assessment techniques and their application to shearer design," *Mining Science and Technology*, vol. 2, pp. 253–270, 1985.
[6] J. Rostami, L. Ozdemir, and D.M. Neil, "Performance prediction: A key issue in mechanical hard rock mining," *Mining Engineering*, vol. 46, pp. 1263–1267, 1994.
[7] E. Detournay, A. Drescher, and D.A. Hultman, "Portable rock strength evaluation device," United States Patent 5670711, 1997.
[8] N. Bilgin, C. Balci, D. Tumac, C. Feridunoglu, and H. Copur, "Development of a portable rock cutting rig for rock cuttability determination," *In: Zhao J, Labiouse V, Dudt JP, Mathier JF (Eds) European rock mechanics symposium EUROCK 2010*, Lausanne, pp. 405–408, 2010.
[9] M. Entacher, S. Lorenz, and R. Galler, "Tunnel boring machine performance prediction with scaled rock cutting tests," *International Journal of Rock Mechanics and Mining Science*, vol. 70, pp. 450–459, 2014.
[10] I. McFeat-Smith, and R.J. Fowell, "The selection and application of roadheaders for rock tunneling," *In: Rapid excavation and tunnelling conference*, pp. 261–279, 1979.
[11] N. Bilgin, and K. Shahriar, "Results obtained from tunnel drifting in Golden Horn (In Turkish)," *In: 11TH Scientific and technical mining congress of Turkey*, Ankara, pp. 305-319, 1989.
[12] S. Keles, "Cutting performance assessment of a medium weight road header at Cayırhan coal mine," MSc thesis. Middle East Technical University, Ankara, p 58, 2005.
[13] W.E. Bamford, "Cuttability and drillability of rock," *Civil College Technical Report Engineering Australia*, vol. July, pp. 1-4, 1986.
[14] W.E. Bamford, "Workshop on rock cuttability and drillability," *In: Herget G, Vongpaisal S (eds) International congress on rock mechanics*, Montreal, vol. 3, pp. 1508–1510, 1987.
[15] C. Balci, and N. Bilgin, "Correlative study of linear small and full-scale rock cutting tests to select mechanized excavation machines," *International Journal of Rock Mechanics and Mining Science* , vol. 44, pp. 468–476, 2007.
[16] S. Yasar, "An investigation on cuttability characteristics of some rock and ore from Eastern Black Sea Region," MSc thesis. Karadeniz Technical University, Trabzon, p 105, 2013.
[17] N. Bilgin, D. Tumac, C. Feridunoglu, A.R. Karakas, and M. Akgul, "The performance of a roadheader in high strength rock formations in Kucuksu tunnel," *In: Proceedings of the 31st ITA-AITES World Tunnel Congress*, Istanbul, Turkey. pp. 815–820, 2005.