

CUTTING CHARACTERISTICS OF A DUCTILE ROCK

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ABSTRACT

A rock sample was obtained from an underground lignite mine for the investigation of the cutting characteristics of a ductile rock where the heading is achieved with a roadheader. The rock sample (metasiltstone) was classified according to a pertinent brittleness classification by means of its compressive strength to tensile strength ratio. Two types of drag picks are used for the execution of the experimental campaign on core and block samples of the metasiltstone. The cutting force, the specific energy and the breakout angle variables were investigated. The cutting force-distance histories of cutting trials were compared with the present literature. It was seen that even an extremely ductile rock sample exhibited the characteristics of brittle cutting regime.

Keywords: Brittleness; Brittle regime; Cutting mode; Ductile regime; Roadheaders; Rock cutting.

1 INTRODUCTION

Roadheaders are by far the most widely used partial face rock excavation machines utilized in mining and civil related excavations and these machines can facilitate in a wide range of rock strength up to 120 MPa in widely jointed rock masses. This range can be extended to some degree with the presence of severe jointing. However, a superior cutting performance can be achieved with roadheaders in low strength rocks.

Rock cutting tests provide the basic information about the cuttability of rocks which form the basis for application of these mechanical rock cutting machines [1]. It is widely accepted that two dominant rock cutting regimes are present which are ductile and brittle rock cutting. Brittle or ductile rock cutting phenomenon is believed to be related to the cutting depth where cutting depths shallower than 1 mm corresponds to the ductile rock cutting and higher cutting depths are pronounced with brittle cutting [2-3]. Moreover, ductile and brittle cutting regime might be treated as a material property according to the cutting force histories during a rock cutting test shown in Figure 1 [4]. On the other hand, Gehring (1987) [5] classified rocks according to their brittleness which is computed as the ratio of the uniaxial compressive strength (UCS) to the tensile strength (TS) given in Table 1. Furthermore, present literature includes a various number of studies focusing on the relationships between cutting characteristics of rock materials and various brittleness indices [6-10]. Most of the studies concentrated on the cutting characteristics of the brittle rocks and correspondingly, very low strength ductile rocks did not draw much attention from the researchers.

Table 1. Brittleness classification based on the ratio of UCS to TS [5]

Brittleness Ratio (UCS/TS)	Classification / Failure mode
< 9	Ductile
9-15	Average
> 15	Brittle

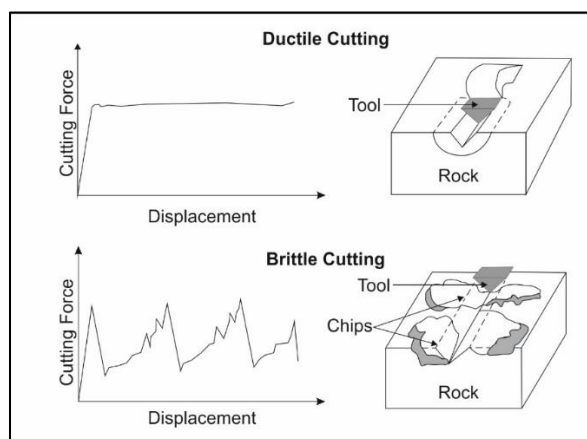


Figure 1. Generic illustration of ductile and brittle rock cutting regime [4]

In this context, a very low strength metasilstone sample was obtained from an underground lignite mine where a roadheader is operated for driving the roadways. Routine rock mechanics tests and mineralogical investigations were carried out to characterize the rock sample. Afterwards, a number of rock cutting tests were realized on the core and block samples of the metasilstone using different types of drag picks (simple chisel and conical picks). Force-distance histories from the rock cutting tests were investigated by means of their cutting regime (ductile or brittle) with the aid of force fluctuations. Moreover, breakout angle, which is an indicator for rock brittleness, of different cutting conditions were investigated. Finally, results were discussed with the present literature.

2 GEOLOGY OF THE LOCATION

The study location is the Çayırhan Coal Basin and it is located 124 km west of Ankara, which holds one of the most significant coal-fired electricity power plants in Turkey. Nearly 520 million tons of lignite reserves are present in the basin [11]. The location map and the geological setting of the coal field is given in Figure 2 along with the stratigraphic section. The coal field mainly consists of claystones, siltstones, conglomerates, tuffs, limestones, lignites, etc. Lignite layers are present in the M1 formation shown in Figure 2.

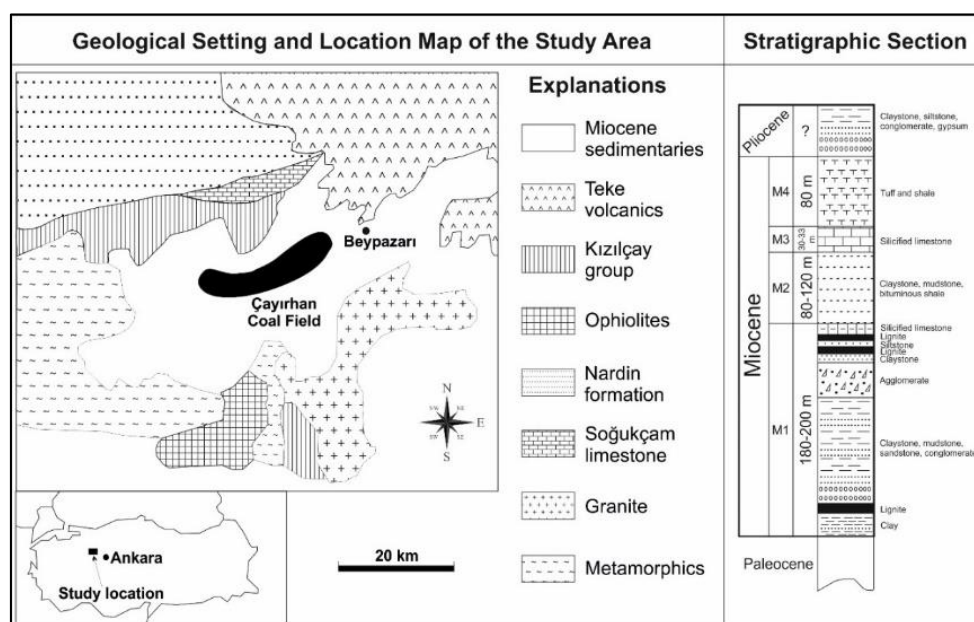


Figure 2. Geological, location map of the underground lignite mine [12], stratigraphic vertical section of the basin [13]

3 SAMPLING

The metasiltstone sample was obtained from a fully mechanized underground lignite mine located in Ankara, Turkey. The underground mining method used is mechanized longwall where a longwall shearer-loader is used for extraction of the coal and performance of the cutting machines used in this region, which has been studied by several authors [14-16]. The roadways, on the other hand, are excavated using different types of roadheaders. The sampling study was carried out in a roadway of which the geological map is given in Figure 3, where a Dosco Mk-2B roadheader is used. As seen from Figure 3, metasiltstone is located between two lignite layers and the sample was acquired from this layer. The sample was carefully wrapped with stretch film to preserve its natural moisture content.

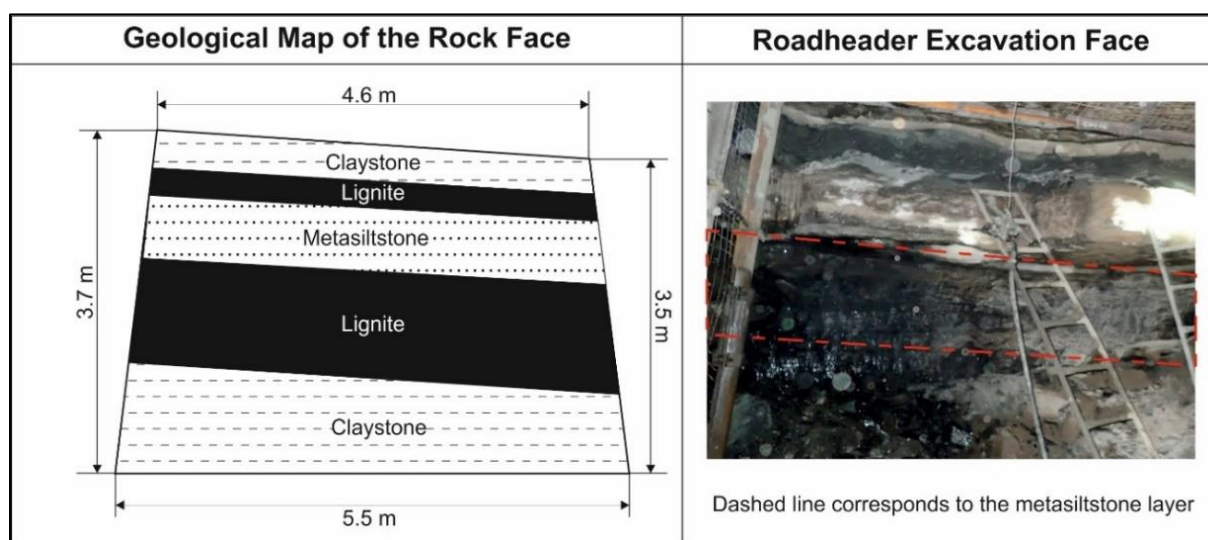


Figure 3. Geological map of the sampling rock face

Thin section and mineralogical examinations were carried out to describe the sample. The metasiltstone sample has a fragmental and foliated texture and it consists of quartz, biotite, muscovite, sericite and plagioclase minerals. The distribution of the minerals is homogenous, and the rock sample was undergone to a low-grade metamorphism and the foliation of the rock is a result of this metamorphism.

4 MECHANICAL PROPERTIES

The metasiltstone sample was subjected to uniaxial compressive strength and indirect tensile strength tests. Strength tests were realized according to the recommendations of ISRM [17]. Uniaxial compressive strength tests were carried out on the core sample having a height to diameter ratio of 2.5, where diameters of the cores are 54 mm. Three replications were accomplished due to the limited size of sample and results were averaged.

On the other hand, indirect tensile strength tests were realized using the Brazilian disc method. Core discs having height to diameter ratio of 0.5 were employed in the tensile strength tests. Five replications were achieved, and results of the individual tests were averaged. Both compressive strength and tensile strength values of the rock sample exhibited a low standard deviation. Uniaxial compressive strength (UCS), indirect tensile strength (TS) and brittleness ratio (UCS/TS) of the metasiltstone are given in Table 2. As it is clear from the table, brittleness ratio (UCS/TS) of the metasiltstone is extremely low, according to the Gehring's (1987) [4] classification, this rock is regarded as a ductile rock sample. Even though, the most reliable method for investigating the brittle or ductile characteristics of a rock sample is a complete stress-strain curve in a compressive strength test, a classification according to [4] was preferred for the sake of simplicity. Additionally, the metasiltstone is a very low strength rock according to Bieniawski (1973) [18].

Table 2. Results of the mechanical strength tests

UCS (MPa)	TS (MPa)	UCS/TS	Brittleness Class
1.89 ± 0.25	0.67 ± 0.11	2.81	Ductile

5 ROCK CUTTING TESTS

Rock cutting tests were carried out in vertical rock cutting rig (VRCR) which is an attachment to the hydraulic bending machines. Two types of drag picks were used in the rock cutting tests which are the simple shaped chisel pick and the conical pick. Experimental procedures and tool specifications were demonstrated in Figure 4.

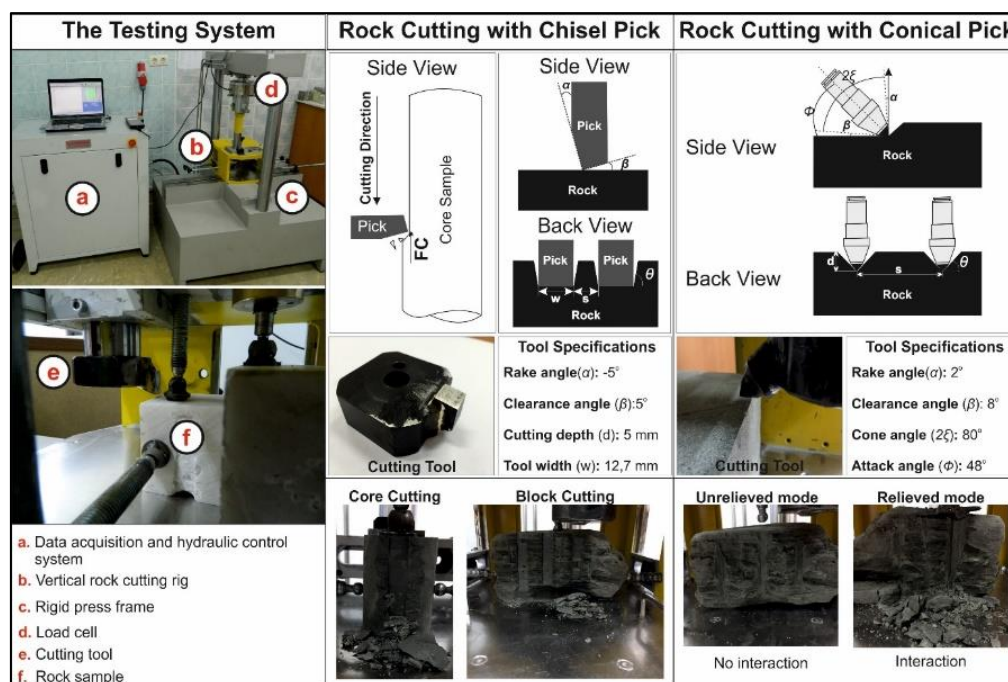


Figure 4. Illustration of the testing system and cutting conditions with different cutting tools

At the first stage, core samples having 54 mm diameter were subjected to rock cutting from 5 mm cutting depth with a negative rake angled simple shaped chisel pick, which is the standard tool for the suggested method of McFeat-Smith and Fowell (1979) [19]. The cutting tests were replicated three times. The same methodology was used for cutting the block samples. Accordingly, block samples were cut three times with a chisel pick.

Additionally, the metasiltstone sample was excavated with a conical pick both in the relieved and in the unrelieved mode. Cutting depth was selected as 9 mm since minimum specific energy was obtained near 9 mm [20-21]. In the relieved cutting tests, spacings between adjacent cuts were changed to locate the optimum spacing (s) to cutting depth (d) ratio. The unrelieved tests were replicated three times. Following each test, the cutting force (FC) which is in the direction of movement is measured by the system and FC versus time/distance history is recorded. Afterwards, specific energy (SE) of the individual cutting trials were calculated with the formula below.

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

where: SE – specific energy $\left[\frac{MJ}{m^3}\right]$,
 FC – average cutting force [kN],
 V – excavated rock debris $\left[\frac{m^3}{km}\right]$.

In addition to FC and SE , breakout angle (θ), which is a relative measure of the brittle character of a rock sample, is measured. Results of the rock cutting tests are summarized in Table 3.

Table 3. Results of the cutting tests

Cutting Condition	d [mm]	s [mm]	s/d	FC' [N]	FC [N]	FC'/FC	SE [MJ/m ³]	θ [°]
Chisel pick on core samples	5	-	-	351.23	130.20	2.70	1.18	-
	5	-	-	334.70	149.46	2.24	1.40	-
	5	-	-	379.78	211.22	1.80	1.96	-
Chisel pick on block samples	5	-	-	299.88	169.68	1.77	2.09	54
	5	-	-	322.03	141.16	2.28	1.19	24
	5	-	-	350.64	123.35	2.84	1.22	34
Conical pick tests (unrelieved)	9	-	-	633.60	377.87	1.68	2.17	25
	9	-	-	711.42	448.71	1.59	2.24	22
	9	-	-	705.72	462.72	1.52	2.68	25
Conical pick tests (relieved)	9	27	3	1078.65	555.56	1.94	2.68	-
	9	36	4	701.81	372.76	1.88	1.38	-
	9	45	5	705.27	348.17	2.03	1.70	-
	9	72	8	683.43	429.77	1.59	2.36	-

6 DISCUSSIONS

Discussion on the force-distance histories

Figure 5 demonstrates the cutting force-distance histories of the individual cutting trials. The maximum cutting force (FC'), as seen in Figure 5, is the average of the three largest peaks [22] and the mean cutting force (FC) is the mean of the all force data available in the force-distance history. FC'/FC ratio is the relative representator of the force fluctuations and gives valuable tips about the cutting characteristics of a rock, i.e. the brittle or ductile rock cutting regimes. Additionally, it is an important parameter for machine vibrations that higher FC'/FC results in higher vibration due to the fluctuations in the cutting force, and higher FC'/FC ratios make excavation harder [23].

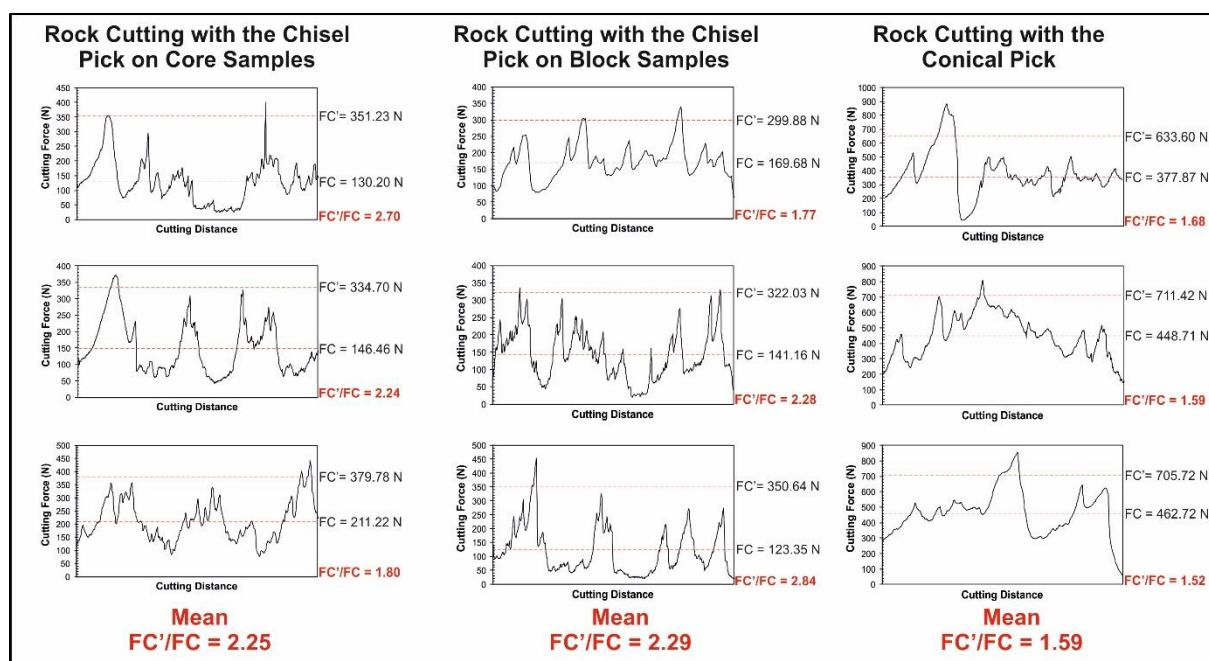


Figure 5. Force-distance histories

At first glance, chisel pick cutting tests gleaned similar histories for both block and core samples and average FC'/FC ratios are 2.25 and 2.29 for chisel pick cutting trials. In a previous study, it has been stated that FC'/FC for positive rake angled chisel picks was changed practically between 1.5-2.5 for 1-6 mm cutting depths and was increased with increasing cutting depth [24]. The force-distance histories and the FC'/FC ratios of the extremely ductile metasiltstone are, therefore, similar with the brittle medium strength rocks.

On the other hand, conical pick cutting histories showed interesting results. For medium strength rocks, it has been evidenced that the FC'/FC ratio for conical picks did not change and are higher than fluctuations in chisel pick cutting, i.e. over 2.5 [21]. However, FC'/FC of the metasiltstone in conical pick cutting showed lower values when compared with the brittle medium strength rocks, which corresponds to less fluctuation.

Generic illustrations of the force-distance histories of brittle and ductile cutting were shown in Figure 1, which had been, previously, proposed by Verhoef et al. (1996) [4]. Ductile cutting regime was pronounced with a steeply rising cutting force which levels to a constant force value over the entire cutting distance. On the other hand, brittle regime was characterized with force fluctuations and each force peak corresponds to a chip formation, so the brittle regime is a result of brittle chipping instead of a ductile flow, even though it is a well-known fact that the peak force is not a result of chip formation alone [25-26]. Ductile cutting regime should, theoretically, glean a FC'/FC value of 1, since there is no force fluctuation. However, the metasiltstone cutting tests revealed that even an extremely ductile rock material ($UCS/TS=2.81$) could not provide a ductile cutting regime by means of force-distance history. The brittle or ductile cutting regimes should be investigated as an experimental condition (i.e. cutting depth) as stated by Richard et al. (2012) and He et al. (2017) [2-3].

Discussion on the breakout angle

In cutting of a plastic material such as steel or soil, the pick, generally, ploughs a surface of its own cross section. However, overbreak is a phenomenon observed in the cutting of brittle materials such as ceramics or rocks which means that a pick sweeps an area more than its cross section. The breakout angle can be regarded as a relative indicator of brittleness of the sample [27]. Lower the breakout angle means higher the brittleness of the rocks, and it plays a key role in the interaction between adjacent cuts in relieved cutting. Performance prediction of the excavation machines may rely on the results of the relieved cutting tests in laboratory. Optimum or minimum SE is being searched for different values of s/d . Figure 6 shows the results of the relieved cutting tests on the metasiltstone with the conical pick and it can be seen that optimum s/d was found as 4 where this ratio varies between 3 and 5 for rocks, and generally increases with brittleness of the rock [8, 20-21]. Breakout angle of the metasiltstone in chisel pick cutting is 38 and in conical pick cutting 24 which are similar with brittle rocks [27].

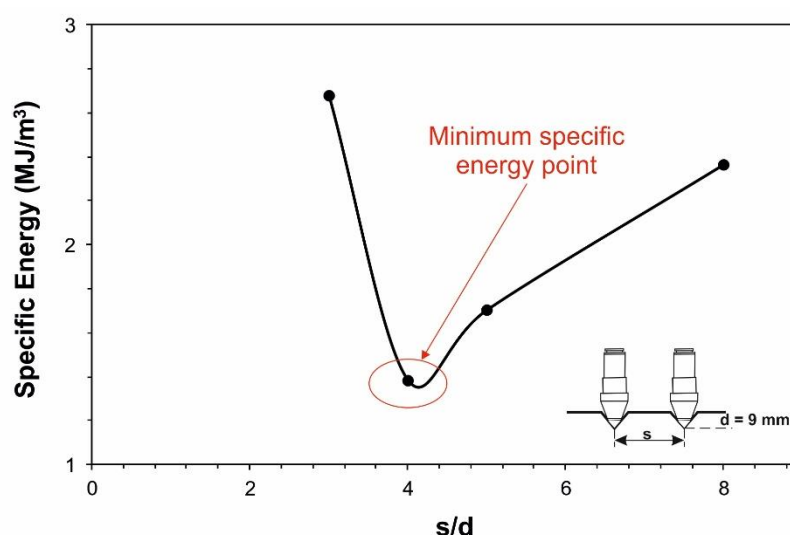


Figure 6. Variation of SE with s/d ratio

7 CONCLUDING REMARKS

A ductile rock, metasiltstone, was excavated in the laboratory with a chisel and a conical pick. Brittle character of a cutting can be pronounced with the force fluctuations in a rock cutting test, i.e. higher fluctuation means higher brittleness. Generic schemes of force-distance histories are present in the mechanical rock cutting literature. However, it was shown in this study that the metasiltstone which is an extremely ductile (UCS/TS=2.81) and a very low strength (UCS= 1.89 MPa) rock did not show a ductile cutting characteristic, which is the soundest outcome of this paper. Previously proposed ductile cutting regime history can be observed in very shallow cutting depths (such as 1 mm or lower). Furthermore, optimum spacing to depth ratio of the metasiltstone was observed to be similar with a brittle rock.

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REFERENCES

- [1] YASAR, S. Determination of optimum rock cutting data through single pick cutting tests. *Géotechnique Letters*. 2019, 9(1), pp. 8–14. DOI: <https://doi.org/10.1680/jgele.18.00124>
- [2] RICHARD, T., F. DAGRAIN, E. POYOL and E. DETOURNAY. Rock strength determination from scratch tests. *Engineering Geology*. 2012, 147–148, pp. 91–100. DOI: <https://doi.org/10.1016/j.enggeo.2012.07.011>
- [3] HE, X., C. XU, K. PENG and G. HUANG. On the critical failure mode transition depth for rock cutting with different back rake angles. *Tunnelling and Underground Space Technology*. 2017, 63, pp. 95–105. DOI: <https://doi.org/10.1016/j.tust.2016.12.012>
- [4] VERHOEF, P.N.W., J.J. OCKELOEN and W.G.M. van KESTEREN. The significance of rock ductility for mechanical rock cutting. In: *Rock Mechanics, Tools and Techniques. Proceedings of the 2nd North American Rock Mechanics Conference, Montreal, June 19-21, 1996*. pp. 709-716.
- [5] GEHRING, K.H. *Rock testing procedures at VA's geotechnical laboratory in Zeltweg*. Internal Report TZU 41. Zeltweg: Voest Alpine, 1987.
- [6] GOKTAN, R.M. Brittleness and micro scale rock cutting efficiency. *Mining Science and Technology*. 1991, 13(3), pp. 237–241. DOI: [https://doi.org/10.1016/0167-9031\(91\)90339-E](https://doi.org/10.1016/0167-9031(91)90339-E)
- [7] KAHRAMAN, S. Correlation of TBM and drilling machine performance with rock brittleness. *Engineering Geology*. 2002, 64(4), pp. 269–283. DOI: [https://doi.org/10.1016/S0013-7952\(01\)00137-5](https://doi.org/10.1016/S0013-7952(01)00137-5)
- [8] COPUR H., N. BILGIN, H. TUNCDEMIR and C. BALCI. A set of indices based on indentation tests for assessment of rock cutting performance and rock properties. *Journal of South African Institute of Mining and Metallurgy*. 2003, 103(9), pp. 589–600.
- [9] GOKTAN, R.M. and N. GUNES. A semi-empirical approach to cutting force prediction for point-attack picks. *Journal of South African Institute of Mining and Metallurgy*. 2005, 105(4), pp. 257–263.
- [10] EBRAHIMABADI, A., K. GOSHTABI, K. SHAHRIAR and M.C. SEIFABAD. A model to predict the performance of roadheaders based on the rock mass brittleness index. *Journal of South African Institute of Mining and Metallurgy*. 2011, 111(5), pp. 355–364.
- [11] TATAR, C., C. HELVACI, H. KÖSE and F. SIMSIR. Geology of the lower and upper coal seams and the mining methods at Çayırhan coal basin, Beypazarı, Turkey. *Mining Engineering*. 1993, 45(8), pp. 1071–1076.
- [12] YAGMURLU, F., C. HELVACI and U. INCI. Depositional setting and geometric structure of the Beypazarı lignite deposits, Central Anatolia, Turkey. *International Journal of Coal Geology*. 1988, 10, pp. 337–360.
- [13] AYDIN, Y. and J. FUNFSTUCK. Beypazarı project report (in Turkish). In: *Proceedings of the Sixth Coal Congress of Turkey, January 1988*. Chamber of Mining Engineers of Turkey, pp. 53–71.
- [14] EYYUBOGLU, E.M. *Effect of Cutting Head Design on Roadheading Machine Performance at Çayırhan Lignite Mine*. Ankara, 2000. Ph.D. thesis. Middle East Technical University.
- [15] KELES, S. *Cutting Performance Assessment of a Medium Weight Roadheader at Çayırhan Coal Mine*. Ankara, 2005. M.Sc. thesis. Middle East Technical University.

- [16] KAHRAMAN, E. and S. KAHRAMAN. The performance prediction of roadheaders from easy testing methods. *Bulletin of Engineering Geology and the Environment*. 2015, 75(4), pp. 1585–1596. DOI: <https://doi.org/10.1007/s10064-015-0801-2>
- [17] ULUSAY, R. and J.A. HUDSON. *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring; 1974-2006*. Ankara: ISRM Commission on Testing Methods, 2007. ISBN 9789759367541.
- [18] BIENIAWSKI, Z.T. Engineering classifications of jointed rock masses. *Transactions of South African Institution of Civil Engineers*. 1973, 15(12), pp. 335–345.
- [19] MCFEAT-SMITH, I. and R.J. FOWELL. The selection and application of roadheaders for rock tunneling. In: *Proceedings of the Rapid Excavation and Tunnelling Conference, Atlanta, Georgia, June 18-21, 1979*. New York: American Institute of Mining, Metallurgical, & Petroleum Engineers, Society of Mining Engineers, 1979, pp. 261–279.
- [20] BILGIN, N., M.A. DEMIRCI, H. COPUR, C. BALCI, H. TUNCDEMIR and N.A. AKCIN. Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results. *International Journal of Rock Mechanics and Mining Sciences*. 2006, 43(1), pp. 139–156. DOI: <https://doi.org/10.1016/j.ijrmms.2005.04.009>
- [21] YASAR, S. and A.O. YILMAZ. Vertical rock cutting rig (VRCR) suggested for performance prediction of roadheaders. *International Journal of Mining, Reclamation and Environment*. 2019, 33, pp. 149–168. DOI: <https://doi.org/10.1080/17480930.2017.1363482>
- [22] BARKER, J.S. A laboratory investigation of rock cutting using large picks. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. 1964, 1(4), pp. 519–534. DOI: [https://doi.org/10.1016/0148-9062\(64\)90059-2](https://doi.org/10.1016/0148-9062(64)90059-2)
- [23] COOK, N.G.W. Analysis of hard rock cuttability for machines. In: *Rapid Excavation – Problems and Progress: Proceedings of the Tunnel and Shaft Conference, Minneapolis, Minnesota, May 15-17, 1968*. Minneapolis: Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, 1970, pp. 39–54.
- [24] YASAR, S. and A.O. YILMAZ. Rock cutting tests with a simple-shaped chisel pick to provide some useful data. *Rock Mechanics and Rock Engineering*. 2017, 50, pp. 3261–3269. DOI: <https://doi.org/10.1007/s00603-017-1303-2>
- [25] BAO, R.H., L.C. ZHANG, Q.Y. YAO and J. LUNN. Estimating the peak indentation force of the edge chipping of rocks using single point-attack pick. *Rock Mechanics and Rock Engineering*. 2011, 44 (3), pp. 339–347. DOI: <https://doi.org/10.1007/s00603-010-0133-2>
- [26] YASAR, S. and A.O. YILMAZ. Drag pick cutting tests: A comparison between experimental and theoretical results. *Journal of Rock Mechanics and Geotechnical Engineering*. 2018, 10(5), pp. 893–906. DOI: <https://doi.org/10.1016/j.jrmge.2018.02.007>
- [27] COPUR, H. Linear stone cutting tests with chisel tools for identification of cutting principles and predicting performance of chain saw machines. *International Journal of Rock Mechanics and Mining Sciences*. 2010, 47(1), pp. 104–120. DOI: <https://doi.org/10.1016/j.ijrmms.2009.09.006>