www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

Arch. Min. Sci. **64** (2019), 4, 797-812

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2019.131067

OKAN SU*#

EVALUATION OF VARIOUS MINING EQUIPMENT USED FOR ROADWAY DEVELOPMENT IN COAL MINES

OCENA EFEKTYWNOŚCI SPECJALISTYCZNEGO SPRZĘTU GÓRNICZEGO UŻYWANEGO DO DRĄŻENIA CHODNIKÓW W KOPALNIACH WĘGLA

This study attempts to evaluate the field performance of various mining equipment used at the development galleries of coal mines. These are hand-held and jumbo rock drills, and a roadheader used in mechanical excavation. For this purpose, the penetration rates of rock drills were monitored and measured in the field. The physical, mechanical, and drillability properties were determined through the collected samples in order to understand the complex interactions between the rock and bit/pick. The abrasive mineral content was also analyzed with XRD analysis to examine the wear on the cutting/drilling tools. Besides, the specific energy of the equipment was calculated relying on the operational parameters. A comparison of the monthly advance and production rates of the drilling rigs and roadheader was made. The relations among operating power, specific energy, and design of buttons/picks were investigated. It has been found that the average advance and production rates of the mining equipment are consistent with the penetration rate. The results verified that the roadheader used in mechanical excavation and the jumbo drill used in drilling and blasting technique are the machines maximizing the advance and production rates.

Keywords: production rate, penetration rate, blasthole drilling, mine roadway, rock excavation

W artykule podjęto próbę oceny efektywności pracy sprzętu górniczego rozmaitego typu, wykorzystanego do drążeniach chodników w kopalniach węgla, np. wszelkiego rodzaju urządzeń wiertniczych od wiertarek ręcznych po wozy wiertnicze oraz urządzenia do drążenia tuneli i wyrobisk. W tym celu monitorowano i mierzono skuteczność i tempo penetracji skał przy użyciu urządzeń ręcznych oraz wozów wiertniczych w warunkach terenowych. Własności fizyczne, mechaniczne oraz urabialność skał określano na podstawie badania zebranych próbek, co umożliwia pełniejsze zrozumienie złożonych oddziaływań pomiędzy skałą a wiertłem/ końcówką. Zawartość substancji ściernych określono w oparciu o metodę analizy rentgenowskiej dyfrakcyjnej (XRD) i na tej podstawie określano zużycie narzędzi wiertniczych i urabiających. Poziom energii rozporządzalnej obliczono w oparciu o parametry eksploatacyjne sprzętu. Porównano miesięczne wyniki postępu i wydajności pracy poszczególnych urządzeń wiertniczych i urzą-

* ZONGULDAK BULENT ECEVIT UNIVERSITY, DEPARTMENT OF MINING AND MINERAL EXTRACTION, 67100, ZONGULDAK, TURKEY

Corresponding author: okansu@beun.edu.tr

dzenia do drążenia tuneli. Zbadano zależności pomiędzy wydajnością roboczą i energią rozporządzalną a konstrukcją końcówek odpowiednich narzędzi. Stwierdzono że średni postęp i średnia wydajność robocza urządzeń idą w parze z tempem wnikania (penetracji skał). Uzyskane wyniki potwierdziły, że maksymalny postęp pracy i wydajność produkcji osiągnąć można dzięki zastosowaniu urządzenia do drążenia tuneli wykorzystywanego do drążenia wyrobisk, wozów wiertniczych do prac otworowych oraz technik strzałowych.

Słowa kluczowe: wydajność produkcji, tempo penetracji skał, prace strzałowe, wyrobiska skalne, drążenie tuneli

1. Introduction

On the development headings of tunnels and underground galleries, the method of excavation and mining equipment have a varying effect on the advance rates. Physical rock properties, rock mass properties, and petrographic properties may lead to different drilling/cutting characteristics of the equipment and influence its efficiency as well as machine utilization ratio. Therefore, cuttability or drillability characteristics of rocks should be investigated in detail and a proper method with the excavation machine should be selected. Yavuz (2015) reported that equipment selection is an important task in mine planning and design due to its operational costs.

If the drilling and blasting technique is found to be economical and practical, hand held or jumbo drills are common machines to drill the blastholes in mining. The hole size, type of rock, cross-section of opening, and rock structure are crucial to determine the type of drilling and equipment to be used. However, if operational conditions are suitable, a roadheader can also be employed as part of mechanical excavation. In this sense, prior to the excavation process, rock strength, hardness, rock matrix, faults, ground water and so on should be examined in detail to obtain maximum cutting efficiency.

In classical methods, the drilling time of rock drills accounts for 15-20% of the total excavation progress. On the other hand, mechanical equipment such as a roadheader can excavate the same rock at a faster advance rate although its applicability is limited from soft to medium-strength rocks. The picks can be worn at the early stages of the excavation (Saeidi et al., 2015). Moreover, larger cross-sectional areas are necessary to install the machine regardless of the ground conditions. Both the classical and mechanical excavation techniques can be compared in terms of occupational safety, economy, and technology as given in Table 1.

TABLE 1

Comparison of classical drilling & blasting and mechanical excavation techniques

Drill & blast technique	Mechanical excavation
• No matter what type of mineral exists within the rock	• Abrasive minerals increase the pick consumption and costs
• Slow advance rates	• Rapid advance rates for most of the rock types
• Random muck size	• Muck size is uniform
• Explosive transportation is dangerous	• No explosive is transported
• High ground and surface disturbance	• Low ground and surface disturbance
• High labor during excavation	• Less labor
• Low capital costs	• High capital costs

Brino et al. (2013) carried out a comparison of both methods in terms of their technical and economic aspects in gypsum quarries. It was found that the roadheader is more appropriate for excavation in gypsum instead of the drill and blast technique due to its minimum wear of the tools, excellent self-support, and 25% lower costs. Ocak and Bilgin (2010) conducted a comparative study of different excavation techniques including impact hammers, roadheaders, and drill & blast. They emphasized that the drill and blast technique is very efficient in high strength rocks. Besides, it has been shown that the roadheader can be more productive than impact hammers in terms of production rates and machine utilization time in weaker rocks. It is also interesting that Tokiwa et al. (2011) used a roadheader to open a ventilation shaft, which was 4.5 m in diameter, in mudstone. Acaroglu and Ergin (2006) pointed out that mechanical systems are more advantageous than conventional methods although the machine stability affects the efficiency of the excavation.

The main objective of this paper is to analyze the penetration, advance, and production rates of the mining equipment and also discuss their effects on the machine parameters such as operating power and specific energy.

2. Field and experimental tests

Turkish Hardcoal Enterprises (TTK) is a state-owned enterprise that operates the mining facilities throughout an area with steeply pitching coal seams in a hilly topography, i.e. the Zonguldak Hardcoal Basin. It is characterized as the largest and deepest basin in Turkey. TTK manages five collieries, which are Karadon, Kozlu, Uzulmez, Amasra, and Armutcuk. Three of them are located at Zonguldak province in the northwest of Turkey, whereas Amasra and Armutcuk collieries are located at Bartın and Eregli province, respectively. Longwall advancing and caving methods are commonly applied throughout the mining areas since those are suitable to the faulted and folded conditions.

Although there were 145 coal seams before, coal production has been mostly completed and there have been approximately 47 active seams lately in the basin (Bicer, 2011). Seams have high slopes ranging from 10° to 70° and their mineable thickness vary from 0.8 to 10 m. Implementation of mechanization systems is very limited due to the complicated nature of deposits, geological structure and higher amount of abrasive minerals in coal measure rocks. The fractures and cleats also govern the excavation efficiency (Pan et al., 2014). These are some reasons limiting the application of mechanical excavation techniques in the basin. Although innovative methods such as "ANSCH" mechanization system and high pressure air blasting technology were applied in the past, they were later stopped due to the lack of experience. Thus, hand-held drills have been applied in coal production for decades. However, the improvement on some mechanical excavation techniques has led Amasra colliery to consider their advantages, especially in terms of their higher production rates (Bilgin et al., 2010).

The amount of annual coal production of TTK was more or less than 2.3 billion tons 10 years ago although the saleable part of it was approximately 1.5 billion tons in total. It has been under 1 billion tons as of 2015. There has been no important investment made by the Turkish government in recent years, thus, a downward trend has been followed in coal production. If the budgets keep on being reduced and no new investments are made, it is a fact that significant drops will be underway. A similar output can also be derived from the advance rates of roadway developments in TTK due to difficult and faulty geological conditions (Fig. 1).

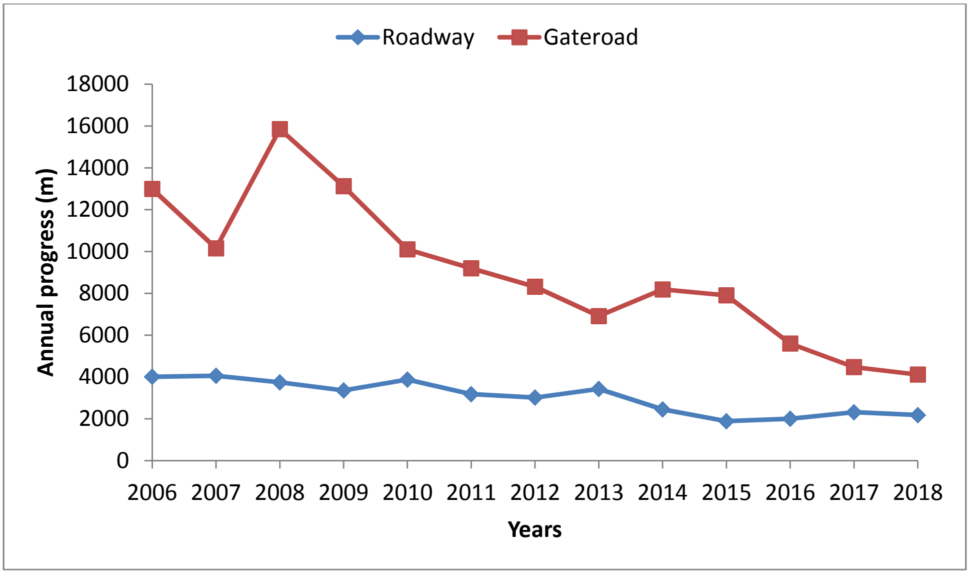


Fig. 1. Annual progress of mine roadways and gateroads in TTK

The best progress in the last decade was achieved in 2008, yet a downward trend has been observed since then in TTK. It is due to deepening the shafts in Karadon and Kozlu collieries and starting the mining operations in new panels at deeper levels. However, the average advance rates of mine roadways and gateroads are calculated to be 3227 m/year and 9993 m/year, respectively.

2.1. Field monitoring of rock drills

The coalfield of TTK covers fine grained sandstone, limestone, and siltstone. The amount of quartz content in sandstone is more or less around 50-60% which increases the wear on the bits. In addition, many anticlines and synclines exist in the coalfields. The thicknesses and the slopes of the seams are also very high. These reasons limit the application of mechanical excavation in the basin. Thus, roadheaders or continuous miners could not be adopted for the excavation of neither the coal nor the rocks. Accordingly, the drill and blast technique has been applied for developing the mine roadways and gateroads of TTK where the blastholes are drilled by using either hand-held or jumbo drills. Su et al. (2013) measured the penetration rates of those rock drills in sandstone and conglomerate rocks in TTK. The field tests were carried out in the roadways of Kozlu colliery at the level of –560 m by employing button bits.

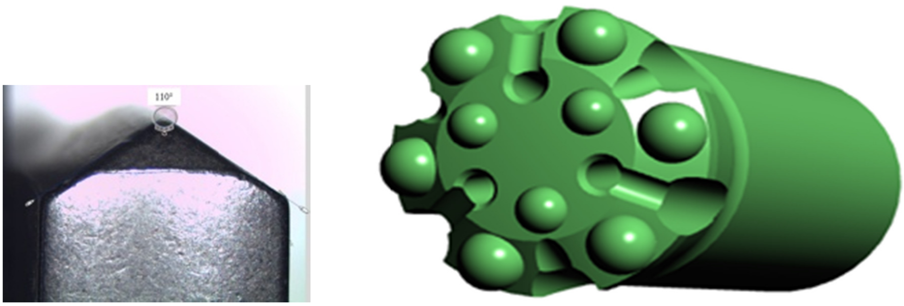
As the gateroads are generally narrow, i.e. 5 m^2 or 10 m^2, portable hand-held rock drills are employed to drill the blastholes in TTK. However, roadways are developed by both jumbo drills and hand-held drills since the cross section areas are larger. The basic experience is to organize the machines well to make them to run at the highest time utilization ratio possible. Thus, good progress can be achieved.

There are two jumbo drills actively operating in Karadon and Kozlu collieries, yet there are many hand-held drills available in TTK. In this context, penetration rates of jumbo and hand-held

(HH) drills were measured at Karadon, Uzulmez, and Kozlu collieries. The penetration rate is of interest to the drill operators because they do not have any equipment to estimate it on site. It directly affects the production capacity (Kricak et al., 2015).

Before the drilling tests in the field, the in-situ hardness of the face was tested by N-type Schmidt hammer. Accordingly, average hardness values at Karadon, Uzulmez, and Kozlu collieries were found to be 39, 45, and 41 respectively which reveal that the rock mass properties of an excavation area have almost the same strength.

The penetration rates of the hand-held rock drills were then measured in the roadways of Kozlu and Uzulmez collieries where the holes were drilled in the length of 170 cm and 100 cm, respectively A new chisel bit, 32 mm in length with a taper angle of 110°, was mounted on the hand-held drill in Uzulmez (Fig. 2a). However, the one in Kozlu was slightly worn. The penetration rate of a jumbo drill was later measured in Karadon colliery in the longer holes having the length of 1.9 m. The roadways in Karadon colliery have the cross section area of 14 m^2 and approximately 45-50 holes are drilled in fine-grained sandstone by button bits with a diameter of 28 mm (Fig. 2b).



(a) Chisel bit (b) Button bit

Fig. 2. Bits mounted on the rock drills

During the field studies, drilling time of the rock drills were monitored and recorded. Thereafter, the depth of blasthole was measured by using a telescopic-meter. The penetration rates (m/min) were calculated by dividing the depth of the hole to the drilling time. 20 holes were drilled at each location. Accordingly, average penetration rates of jumbo drills in Karadon and Kozlu were found to be 1.66 m/min and 1.44 m/min, respectively. Furthermore, average penetration rates of the hand-held drills were calculated to be 0.24 m/min both in Uzulmez and in Kozlu collieries. The variations of the rates are illustrated in Fig. 3.

As can be seen from Fig. 3, a downward trend on the penetration rates from 1.93 m/min to 1.30 m/min occurred due to the wear on the bit. The XRD analysis shown in Fig. 4 also validates this finding since the rocks include abrasive minerals. The average penetration rate of the jumbo drill is measured to be 1.66 m/min. Su et al. (2013) also performed the drilling tests by using the same type of jumbo drill in Kozlu and the average penetration rate was calculated to be 1.44 m/min. According to Fig. 3, it is clear that a jumbo drill is 6 times faster than the hand-held drill.

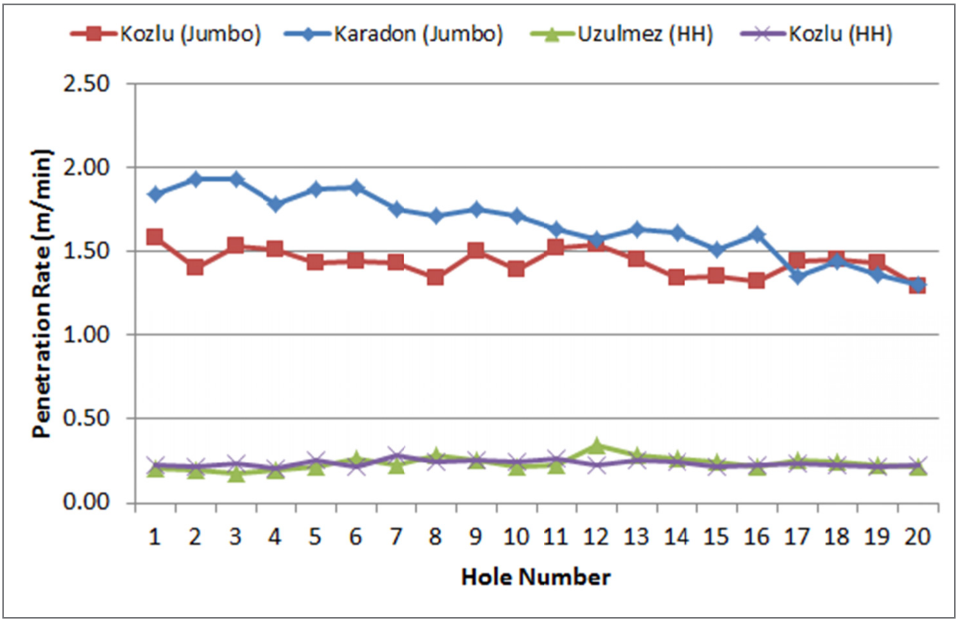


Fig. 3. Variation of the penetration rates in the roadways

2.2. Experimental tests

In addition to in-situ hardness and drilling test, mechanical and drillability properties of the sandstone were tested in the laboratory. For this purpose, uniaxial compressive and Brazilian tensile strength, and drilling rate index of rocks were determined and the results are summarized in Table 2.

TABLE 2

The results of experimental tests

Colliery name	ρ	σ_C	σ_t	E	S_{20}	SJ	DRI
Karadon	2.61	71	13	18.9	38	78	48
Kozlu	2.58	54	7	—	42	102	53
Uzulmez	2.63	75	18	20.0	30	94	43

where ρ is density (kg/m^3), σ_C is uniaxial compressive strength (MPa), σ_t is Brazilian tensile strength (MPa), E is average Young's modulus (GPa), S_{20} is brittleness value, SJ is Sievers' miniature drill value, DRI is drilling rate index.

From the data in Table 2, it is clear that the fine grained sandstones collected from different collieries are in medium-hard strength class. The drilling rate index reveals that drillability characteristic is in the medium category. This result also validates the strength characteristics of rocks. Thus, it can be said that the sandstones collected from three mine collieries exhibit the same mechanical behavior.

On the other hand, wear on the picks is a major problem for the engineers while drilling the abrasive rocks in the coalfields. Erarslan and Ghamgosar (2016) reported that excessive tool wear and machine vibrations are the limiting factors for the application of mechanical equipment in hard rock. The rocks having high abrasive minerals may cause the bits to blunt and wear in a short period. At the same time, it increases the bit consumption on the one hand, and on the other hand, decreases the efficiency of the drilling equipment. For these reasons, the mineralogical content of the samples was determined by XRD analyses.

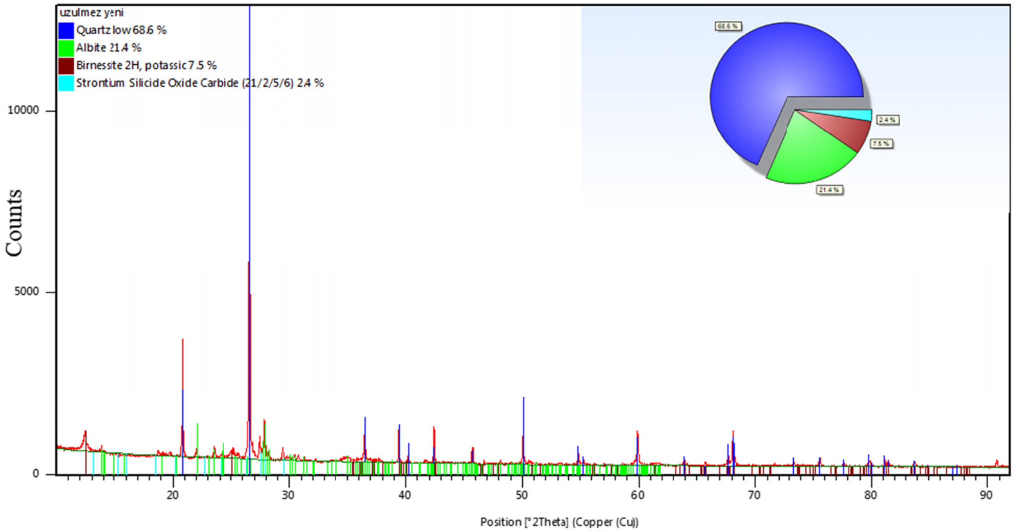


Fig. 4. XRD analysis of the sandstone obtained from Uzulmez colliery

As illustrated in Fig. 4, the quartz content of sandstone is higher than 60% and the rocks also include albite, which is also an important abrasive mineral, in lower percentages. These minerals increased the wear rate of button bits.

3. Specific energy and advance rates of mining equipment

Development headings are significant in underground coal mining. When the galleries are opened faster, higher production rates are ensured from the coal seams. The excavation technique is the most decisive factor at this stage. In this regard, either classical drill and blast or mechanical excavation technique can be applied. Whichever method is selected; the performance of appropriate mining equipment should be evaluated. Power, torque, bit geometry, and essentially specific energy, which is defined as the energy to cut a unit volume of rock, are dominant machine parameters affecting the advance rate. For this reason, the specific energy and the advance rates of some mining equipment are discussed below.

3.1. Hand-held rock drills

Hand-held rock drills are rotary-percussive drilling equipment. They have been broadly preferred in the drill and blast, anchor and rock-splitting processes. They are neither expensive nor too large and generally powered by compressed air. Thus, they can safely and conveniently be used in coal mines although they have stability and durability problems. High pressure air is pumped to the stroke for the impact action and rotation. Hence, the bit is penetrated the rock for efficient drilling. Some types of them are also either electrically or hydraulically powered. The operational parameters of the rock drill employed in TTK are listed in Table 3.

TABLE 3

Technical specifications of hand-held drills used in TTK

Operational parameters	**Value**
Weight (kg)	18
Length (mm)	550
Impact frequency (Hz)	34
Stroke length (mm)	50
Operating pressure (bar)	4-6
Air consumption (m^3/min)	1.44
Piston diameter (mm)	60
Rotational speed (rpm)	210

The blast holes, on average 175 cm long, are drilled by chisel bits with a diameter of 32 mm. Accordingly, the average penetration rate is measured to be 0.24 m/min and the power of the rock drill is calculated to be 0.7 W. Hustrulid and Fairhurst (1971) proposed Equation (1), where specific energy depends upon the penetration rate, impact energy and the frequency of the piston, to calculate the specific energy of percussive rock drills.

$$SE = \frac{E_t \, bpm \, T_r}{A \;\; PR} \tag{1}$$

where E_t is impact energy (Nm), bpm is frequency (blows per minute), T_r is energy transfer coefficient, A is hole area (m^2), PR is penetration rate (m/min).

Moreover, the impact energy, which is proportional to the impact pressure, can be calculated with Equation (2) propounded by Bates (1965).

$$E_t = p \, AS \tag{2}$$

where p is impact pressure (MPa), A is piston area (mm^2), S is stroke of piston (m).

Since hand-held drills are very light and the piston diameters are very short when compared to other rock drills, the energy transfer coefficient can be neglected. Thus, the average specific energy is calculated to be 93.1 MJ/m^3 based on the impact energy of 8.82 Nm estimated by Equation (2).

On the other hand, hand-held rock drills can perform longer holes. However, their stability problem lowers the drilling efficiency and slows down the advance rates. In this sense, the field performance of hand-held drills was monitored for one year in Kozlu and Uzulmez collieries of TTK which had a total cross-section area of 14 m^2. Total progress was recorded every month throughout the year. Accordingly, the average advance rates and excavated volume of each month were calculated. The results are presented in Table 4.

TABLE 4

Average advance and production rates of hand-held rock drills

Months	D	Kozlu		Uzulmez	
		AR	PR	AR	PR
January	26	0.27	3.77	1.23	17.2
February	24	0.95	13.36	0.71	9.92
March	26	2.40	33.65	0.50	7.00
April	25	0.84	11.76	0.92	12.8
May	25	0.28	3.92	1.08	15.1
June	25	0.08	1.12	0.64	8.96
July	24	0.42	5.83	1.29	18.1
August	25	0.76	10.64	0.56	7.84
September	26	0.23	3.23	0.73	10.2
October	23	0.65	9.13	0.70	9.74
November	25	0.18	2.52	0.96	13.4
December	27	0.33	4.67	1.00	14.0
Total	301		104		144.3

where D is number of worked days, AR is average advance rate (m/day), PR is average production rate (m^3/day).

From data in Table 4, it is apparent that the average rate of advance in Kozlu colliery varies from 0.20 to 1 m/day if March and June are excluded. Nevertheless, it ranges from 0.50 m/day to 1.30 m/day in Uzulmez colliery. Besides, the average production rate, i.e. excavated volume of rock, was found to be 8.6 m^3/day in Kozlu. However, it was calculated to be 12.0 m^3/day in Uzulmez colliery. Although it is not a tunnel and the production rate of it is dependent on parameters such as the length of a tunnel, geometry, geological conditions, tunnel dimensions and so on, these results can be considered very low for a coal mine. In Kadikoy-Kartal metro tunnel, Ocak and Bilgin (2010) measured the mean production rate of 187 m^3/day, which is 15-20 times faster than that of a coal mine.

3.2. Jumbo rock drills

Jumbo drills are utilized in various applications of excavation in underground mining such as tunnels, roadways, and gateroads. As the technology improves, the automation on the jumbo has also been computerized. Jumbo drills have the advantage of the exact positioning of booms and drilling a uniform hole depth. They are also more successful in the jointed and faulty faces. The driving speed, maneuverability, and the safety of the machine are much better than those of hand-held rock drills. Therefore, this type of drilling rig is only preferred in the roadways of TTK since their cross-section areas are larger than those of gateroad faces. The one used in Karadon colliery has the operational parameters listed in Table 5.

TABLE 5

Technical and operational parameters of jumbo drill used in TTK

Operational parameters	Value
Impact frequency (Hz)	50
Stroke length (mm)	32
Impact pressure (bar)	100-120
Impact energy (Nm)	150 (at 100 bar impact pressure)
Thrust pressure (bar)	50
Rotation pressure (bar)	70
Oil consumption of percussion (l/min)	60
Piston diameter (mm)	37
Rotational speed (rpm)	300

The machine withdraws the current of 65 A at the voltage of 550 V while drilling the holes. In this context, jumbo gets the power of 65 kW. In light of the parameters given in Table 5, the specific energy is calculated to be 339 MJ/m^3 with Equation 1 where the energy transfer coefficient was assumed to be 0.7.

This rock drill has been used to drill the blast holes in Karadon colliery of TTK for a long time. Besides, another jumbo drill was employed in Kozlu colliery of TTK (Su et al., 2013). Both of the jumbo drills had the same rods length and the same operational parameters. The cross section area of the tunnel was 14 m^2. The average advance rate and average production rate of the rock drills are summarized in Table 6.

TABLE 6

Average advance and production rates in Karadon and Kozlu collieries

Months	D	Karadon		Kozlu	
		AR	PR	AR	PR
January	26	2.25	31.50	2.09	29.24
February	24	2.69	37.63	2.01	28.15
March	26	2.54	35.54	2.48	34.73
April	25	2.70	37.80	3.59	50.29
May	25	2.82	39.48	3.14	43.90
June	25	2.34	32.76	1.68	23.52
July	24	3.62	50.69	0.43	6.07
August	25	3.26	45.64	1.12	15.69
September	26	1.62	22.62	1.16	16.26
October	23	1.74	24.35	1.77	24.83
November	25	3.06	42.84	2.44	34.16
December	27	1.13	15.81	2.40	33.60
Total	301		416.65		340.44

where D is number of worked days, AR is average advance rate (m/day), PR is average production rate (m^3/day).

According to Table 6, the average rate of advance in Karadon colliery was found to be 2.5 m/year while it was approximately 2.0 m/year in Kozlu colliery. In light of these advance rates, the total production rates were found to be over 300 m^3/year. Even the annual production rate is very low when compared to the study of Ocak and Bilgin (2010) since they achieved 187 m^3/day of the mean production rate.

3.3. Roadheader

In addition to rock drills, the performance of a medium duty roadheader from a lignite mine was taken into consideration in order to make a comparison with the classical methods. The machine was 48 tons in weight and it was driven through the cross-section area of 24 m^2 in the trapezoidal shape. The technical features of the axial type roadheader are given in Table 7.

TABLE 7

Technical features of roadheader

Operational parameters	Value
Total installed electric motor power (kW)	224
Cutterhead power (kW)	112
Rotational speed (rpm)	58
Advance speed (m/min)	8.4
Hydraulic system working power (kW)	112
Maximum allowable working slope (°)	14
Ground pressure (MPa)	1.19

The rock formation of the roadways in the mine was not very hard and consisted of coal, clay, and siltstone. The N-type Schmidt hammer values were measured at the face and it was found that the values varied between 24 and 36. The coal and clayed parts were tested to be 24 in the bottom of the face whilst the upper part was measured to be 36. Accordingly, it can be claimed that these rocks were softer than the ones in the development galleries of TTK. The clay caused the advance rate to slow down from time to time.

The roadheader was operated at a voltage of 1100 V. While it was excavating the rock face, the current was measured to be 90 A. Hence, the cutterhead was operated at the power of 99 kW. It was usually driven for maximum 2.5-3.0 hours in a shift. Accordingly, the machine utilization factor was assumed to be 31%. The average advance and production rates were recorded for one year as reported in Table 8.

According to Table 8, the average advance rates of a roadheader ranged from 3 to 8 m/day which is almost 4 times higher than that of the jumbo drill and also 8-10 times higher than a hand held drill. Furthermore, the maximum progress of the roadheader is found to be 237 m, which cannot even be comparable to the other drilling rigs' performance. In total, a development heading of 1.4 km was achieved during one year.

Since the AR and PR given above are the average values of each month, an average production rate of one year could be calculated as 115.1 m^3/day. In this sense, the instantaneous cutting rate can be determined as 4.8 m^3/h by Equation (3). The specific energy is calculated by Equation (4) (Bilgin et al., 2014).

TABLE 8

Average advance and production rates in a lignite coalfield

Months	D	AM	AR	PR	B
January	30	117	3.90	93.60	47
February	24	124	5.17	124.00	25
March	14	48.5	3.46	83.14	1
April	26	104.5	4.02	96.46	1
May	13	48	3.69	88.62	6
June	23	105	4.57	109.57	113
July	26	79	3.04	72.92	103
August	28	100	3.57	85.71	30
September	26	125	4.81	115.38	36
October	19	117	6.16	147.79	36
November	30	237	7.90	189.60	184
December	26	189	27	174.46	137
Total	285	1394			719

where *D* is the number of worked days, *AM* is the total advancement (m), *AR* is average advance rate (m/day), *PR* is average production rate (m^3/day), *B* is the number of bits consumed per month.

$$PR = ICR\ MUT\ S_d\ H_{sh} \tag{3}$$

where *ICR* is instantaneous cutting rate (m^3/h), *MUT* is machine utilization time (%), S_d is number of shifts in a day (shift/day), H_{sh} is shift time (hours/shift).

$$SE = k\frac{P}{ICR} \tag{4}$$

where *SE* is specific energy (kWh/m^3), *k* is energy transfer ratio, *P* is the power of the machine (kW), *ICR* is instantaneous cutting rate (m^3/h).

If k is assumed to be 0.45 for axial type roadheader, the specific energy is also calculated to be 11.25 MJ/m^3. According to the classification suggested by McFeat and Fowell (1977), the roadheader performance is within the moderate-good limits and a consistent cutting performance can be expected which is quite reasonable in the light of data presented in Table 8. However, this finding could not be compared to the drilling rigs since their excavation principle is different.

4. Discussion

In the complex nature of underground mining, developing the galleries is crucial to maximize the advance and production rates. New technologies and machines for the excavation of the galleries have been improved for decades. However, the geologic conditions and unit costs of the mining machines might sometimes be restrictive for the choice of any system. For this reason, cost-effective machines would be preferred.

Both the hand-held and the jumbo drills, which are generally very common for mines and tunnels, have a rotating bit and rod integrated. Their breaking mechanisms are very similar. Bits are rotated under a high level of impact and thrust pressure. The percussion and rotation are transmitted to the bottom of the hole and cracks are formed within the rock. They propagate as the impact energy is transferred through the rod. The thrust against the rock is achieved by the weight of the hand-held drill, which is 18 kg in TTK collieries, whereas it is about 550 kg for the jumbo drills. However, it can also be adjustable by fitting extra weights on the hand-held rock drills. Both machines can be used in medium-hard to hard rock although they are powered by pneumatic and hydraulic systems separately.

Moreover, button bits are more suited to the rotation characteristics of the drilling machine and the round holes are produced with faster drilling rates than chisel bits. The buttons can be arranged in different numbers, shapes, and positions depending on the abrasivity and hardness of the rock. Besides, the taper angle of the chisel bits can be changed. The experience on the design of the bit indicated that the angle of 110° exhibit the optimum performance.

On the other hand, rock drills are not analogous to roadheaders, but they have a few similar aspects. Both the cutters and bits are rotated under a magnitude of thrust. When the rock is hard, the thrust is increased. The conical picks on the cutterhead can be placed in different patterns depending on the rock properties while the button bits can also be designed for the same purpose. Their progress can be monitored in the field in terms of penetration and advance rate.

Furthermore, specific energy is dependent on the mode of rock breakage, the size and the type of equipment used. There are many methods of determining specific energy, but the results are only comparable if the mining equipment and the type of rock mass is the same. For this reason, the results presented in this study give preliminary information about the machine performance and it is not reasonable to make a comparison between the specific energy of roadheaders and drilling rigs. For example, Kalyan et al. (2015) measured the specific energy of cross bits in the laboratory by plotting the force-penetration curves. Their results varied from 200 MJ/m^3 to 800 MJ/m^3 for different rock types. On the other hand, Balci et al. (2004) performed full scale rock cutting tests in order to predict the performance of mechanical equipment by specific energy. His experimental tests on 23 different rock types ranged from 14 MJ/m^3 to 58 MJ/m^3. Bilgin et al. (2004) predicted that the specific energy value of a roadheader can change from 11 to 16 MJ/m^3 in six different zones. Thus, it is apparent that the evaluation of specific energy depends on the cutting equipment. Although both machines can be used for the same purpose, it is better to make a comparison in terms of their penetration and advance rates. In this sense, it can only be stated that the specific energy of the hand-held drill is 3.6 times lower than the jumbo drill, but they are cost-efficient equipment.

One year of monitoring the advance rate of jumbos in Karadon and Kozlu collieries resulted in the advance rates of 2.6 m/day and 2 m/day, respectively. Nevertheless, it was 0.6 m/day and 0.8 m/day for hand-held drills in Kozlu and Uzulmez collieries, respectively. Thus, it can be reported that the advance rates of jumbo drills are 3-4 times faster than hand-held drills in the field.

Besides, the production rates of hand-held, jumbo drill, and a roadheader from a lignite mine were evaluated. The entire results monitored for one year are shown in Fig. 5.

As it can be predicted from Fig. 5, the average net production rate of roadheader is 115.10 m^3/year and it is calculated to be 34.72 m^3/year for jumbo drill and 12.04 m^3/year for hand-held drill. The results reveal that the roadheader equipped with point attack picks can achieve substantially higher production rates. However, due to the complex geologic nature of

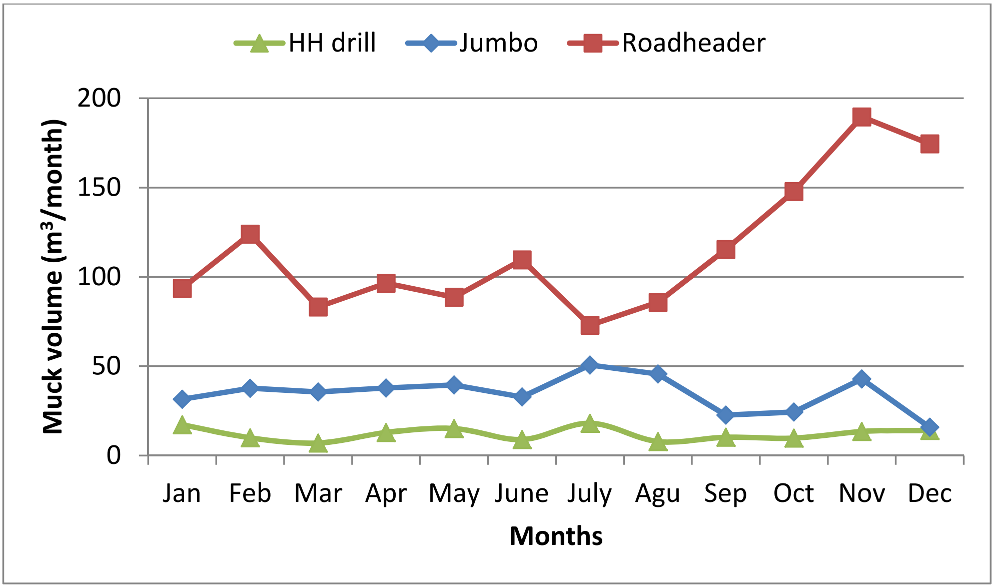


Fig. 5. Variation of production rates in the development heading during one year

underground seams and a high percentage of abrasive minerals in the rocks, the application of a roadheader would be very limited roadway developments in TTK.

5. Conclusions

Mechanical excavation machines are generally too large, too expensive, too restrictive in narrow confines even though there are also some types of small machines operated in underground mines. Most of the large machines could be inadequate due to the confined spaces. It is possible to open larger cross sections by roadheader with higher advance rates. However, when the conditions are not available, conventional methods must be applied with an appropriate drilling carriage.

There are a few numbers of hydraulic jumbo drills in Karadon and Kozlu collieries. They have the penetration rate varying between 1.40 and 1.70 m/min. The roadways and gateroads in other collieries of TTK are generally developed by drilling and blasting method in which the holes are drilled by hand-held rock drills. They can just reach a penetration rate of 0.40 m/min with a daily advance rate ranging from 0.9 m/day to 1 m/day. Nevertheless, the advance rates of jumbo drills vary from 1.60 m/day to 3.60 m/day. Thus, it is apparent that faster penetration, advance, and production rates are obtained by jumbo drills in the galleries.

Moreover, according to the records of the mine collieries, the variations in the production rates were proportional to the penetration rates of the rock drills regardless of the cross sectional area. For this reason, new jumbo drills would definitely provide faster advance rates and hence the coal production would relatively increase in TTK.

On the other hand, it was seen that the advance rate of a roadheader is very high when compared to drilling rigs. For this reason, it is suggested that a detailed petrographic analyses of the rocks surrounding the coal, i.e. not only sandstone but also conglomerate and clay formations, should be performed in the basin in order to ensure the usability of a roadheader for driving the galleries with minimum tool wear and costs. Although there was one unsuccessful experience of roadway development due to improper roadheader selection in Karadon colliery, Hema Energy Group developed successfully three roadways by roadheaders in Tarlaagzı colliery which is close to the Amasra colliery of TTK. Thus, a detailed site investigation of available galleries of TTK should be examined carefully in order to assess the suitability of them.

Acknowledgments

The author would like to acknowledge the support from Scientific Research Project of Zonguldak Bulent Ecevit University for funding this research under Grant No. 2016-29011448-01 and the Turkish Hardcoal Enterprises (TTK) for allowing to perform the field tests.

References

Acaroglu O., Ergin H., 2006. *A new method to evaluate roadheader operational stability*. Tunnelling and Underground Space Technology **21**, 2, 172-179.

Balci C., Demircin M.A., Copur H., Tuncdemir H., 2004. *Estimation of optimum specific energy based on rock properties for assessment of roadheader performance*. Journal of the South African Institute of Mining and Metallurgy **104**, 11, 633-641.

Bates R.E., 1965. *Field results of percussion air drilling*. Journal of Petroleum Technology, March, 257-262.

Bicer N., 2011. *Coalbed methane project in Zonguldak coalfield. 22nd World Mining Congress & Expo*. Eskikaya, Ş. (Ed). Turkish National Committee, Istanbul, Turkey, 623-629.

Bilgin N., Dincer T., Copur H., Erdogan M., 2004. *Some geological and geotechnical factors affecting the performance of a roadheader in an inclined tunnel.* Tunnelling and Underground Space Technology **19**, 6, 629-636.

Bilgin N., Temizyurek I., Copur H., Balci C., Tumac D., 2010. *Cuttability characteristics of TTK Amasra thick seam and some comments on mechanized excavation.* Proceedings of the 17th Coal Congress of Turkey, Zonguldak, Turkey, 217-229.

Bilgin N., Copur H., Balci C., 2014. *Mechanical Excavation in Mining and Civil Industries. 1st edn.* CRC Press, New York.

Brino G., Cardu M., Gennaro S., Gianotti A., 2013. *Technical-economical comparison between excavation by D&B and by roadheader in two underground gypsum quarries.* Proceedings of the 23rd International Mining Congress of Turkey. Celik I.B. and Kilic M.G. (eds). Antalya, Turkey. 813-824.

Erarslan N., Ghamgosar M., 2016. *An innovative and effective approach to hard rock cutting.* Proceedings of Rock Mechanics and Rock Engineering: From Past to the Future, Cappadocia, Turkey. 913-916.

Hustrulid W.A., Fairhurst C., 1971. *A theoretical and experimental study of the percussive drilling of rock. part II force-penetration and specific energy determinations.* International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts **8**, 4, 341-356.

Kahraman E., Erarslan O., 2011. *Evaluation of roadway drivage works in G field at Cayirhan underground mine.* Proceedings of 3rd Mining Machinery Symposium. Kose H. and Gonen A. (eds.) 83-96, Izmir, Turkey.

Kalyan B., Murthy C.S.N., Choudhary R.P., 2015. *Estimation of specific energy in rock indentation test.* International Journal of Research in Engineering and Applied Sciences **5**, 8, 33-47.

Kricak L., Negovanovic M., Mitrovic S., Miljanovic I., Nuric S., Nuric A., 2015. *Development of a fuzzy model for predicting the penetration rate of tricone rotary blasthole drilling in open pit mines.* Journal of the Southern African Institute of Mining and Metallurgy **115**, 11, 1065-1071.

Mcfeat S., Fowell R.J., 1979. *The selection and application of roadheaders for rock tunneling.* Proceedings of 4th Rapid Excavation and Tunneling Conference. Maeviss A.C. and Hustrulid W.A. (eds.), American Society of Civil Engineers, Atlanta 1, 261-279.

Ocak I., Bilgin N., 2010. *Comparative studies on the performance of a roadheader, impact hammer and drilling and blasting method in the excavation of metro station tunnels in Istanbul.* Tunnelling and Underground Space Technology **25**, 2, 181-187.

Pan J.N., Wang H.C., Wang K., Niu Q.H., 2014. *Relationship of fractures in coal with lithotype and thickness of coal lithotype.* Geomechanics and Engineering **6**, 6, 613-624.

Saeidi O., Elyasi A., Torabi S.R., 2015. *Wear Assessment of the WC/CO cemented carbidetricone drillbits in an open pit mine.* Geomechanics and Engineering **8**, 4, 477-493.

Salsani A., Daneshian J., Shariati S., Yazdani-Chamzini A., Taheri M., 2014. *Predicting roadheader performance by using artificial neural network*. Neural Computing and Applications **24**, 7-8, 1823-1831.

Su O., Yarali O., Akcin N.A., 2013. *Comparison of Drilling Performance of Chisel and Button Bits On the Electro Hydraulic Driller.* Rock Mechanics and Rock Engineering **46**, 6, 1577-1587.

Tokiwa T., Tsusaka K., Ishii E., Sanada H., Tominaga E., Hatsuyama Y., Funaki H., 2011. *Influence of a fault system on rock mass response to shaft excavation in soft sedimentary rock, Horonobe area, northern Japan*. Int J of Rock Mechanics and Mining Sciences **48**, 5, 773-781.

Yavuz M., 2015. *Equipment selection based on the AHP and Yager's method.* Journal of the Southern African Institute of Mining and Metallurgy **115**, 5, 425-433.