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Effect of uniaxial compressive strength of rock on penetration rate and bit wear rate of drill

Drillability plays a crucial role in increasing the capability of blasthole drills in drilling and thereby contributing valuable input for the mining industry. The productivity of the mines and the life of the machines are directly dependent on the wear rate of the drill bit. In this light, an investigation was conducted to illustrate the relationship between the uniaxial compressive strength (UCS) of the rock, the penetration rate of the drilling machine and the bit wear-out rate at overburden benches of a surface coal mine. The wear-out rate of drilling bit estimated from digital imaging of the diametrical distribution of button bits obtained from imaging software, that was taken 'Before' and 'After' drilling. The UCS of rock mass was measured using Schmidt Hammer while wear-out rate of the drill bit was measured through computer software. The results obtained from the experimental observations and graphical plot shows that as the UCS (in N/mm^2) increasing from 27.5 to 42.46 the penetration rate (in mm/s) decreases from the 30 to 14 and wear-out rate (in mm^2/meter of the hole drilled) are increasing from 0.339 to 1.05.

Keywords: *Rotary-percussive drilling, uniaxial compressive strength, wear-out rate, penetration rate, drill bits.*

1. Introduction

Rotary-percussive drilling is mostly used in the opencast and underground mines in Indian geo-mining conditions irrespective of the strength of the rock because of the abrasive action of the bits and inhabits resistance to withstand wear due to friction. These drills have industry compatible characteristics such as shock resistance, robust and ability to work in harsh environmental conditions. Many opencast mines perform drilling operations in overburden and coal benches by the rotary-percussive drilling machines. Drilling bit is the essential tool of rotary percussion drills, used in rock indentation process for production and overburden removal in opencast mines. Many mining industries and research organizations have conducted various types of parametrical study on the drilling tools involving machinery parameters and rock characteristics that play a vital role in drilling.

UCS (uniaxial compressive strength) of rocks is a major geo-mechanical factor that affects the drillability of drilling machines and the wear-out rate of the buttons of drilling bit. It is also known as "crushing" strength of the rock material. When the drilling force exceeds the crushing strength, then it tends to break the bonds between grains of rock and forms the chip of rocks with shear or tensile failure of the rock [1].

The penetration rate of drilling machine is the most critical parameter used for fostering productivity in mining industry. Drilling operations of the machines are monitored and checked at regular intervals on the basis of penetration rate of the machines. Penetration rate is also described by the term 'drillability'. It is the overall ability to drill a rock and depends on the geo-mining factors like crushing strength, toughness, chip separation and abrasiveness [1]. The machinery factors that depends on penetration rate were feed force, rotary speed, percussion blow energy and percussion blow frequency [2]. Penetration rate depends on cutting bit parameters mainly the weight of bit, the sharpness of bit, geometrical shape and size of buttons in the bit. It is an important parameter which is involved in mechanical and physical process during excavation [3]. It decides the longevity of the machine and drilling economy while efficiently evaluating mining costs at the preliminary stage of production. Some of the scientific investigations were conducted to understand the mechanism of rock cutting process and thereby derive the parametric relations while incorporating production drilling in the opencast mines, mostly with the rotary-percussion type of machines alongwith button bits.

Drill bit is the quintessential element in the entire process of drilling which undergoes the process of chip formation at the bit-rock interface while exhibiting the mechanism of grinding, crushing and shattering. The material of the bit and the rock surface, and feeding mechanism are the primary mechanical factors governing drilling. Percussion mechanism is the transmission of the kinetic energy from the piston to

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bit in the form of the shock wave in the rocks while exerting thrust for vertical depth advancement of drill bit. While rotational mechanism of the bit executes the cutting of rocks at the periphery between two consecutive blows. Drilling mechanism undergoes percussive action initially for the creation of wedge during crushing of rocks at the bit and rock interface. Penetration rate is directly proportional to the drilling energy which facilitates crushing of the rock into chips. The fragments formed during percussion mechanism were removed by flushing, following penetration due to the rotation of the bit. Penetration rate and wear-out rate are related interdependently to the cuttability of the bit. Therefore, the piston gives the greater performance while influencing the penetration rate [4]. Button bits dressed by grinding the buttons to remove flats and restore their hemispherical shapes [5]. Thus, improvement in the machinery parameters fosters productivity of the mines in a long-run trend alongwith the increase in service life of essential elements.

Bit wear is due to sparing of drilling energy by the bit at the time of wedge formation in the rock surface while drilling machine penetrates the rock by rotary and percussive action for drilling the blastholes. The effect of rocks on bits leads to failure, if drills operated for longer time without maintaining the sharpness, thereby affecting performance of the bit. The purpose of bit conditioning is to optimize the penetration rate and to maximize the bit life [4]. The chip formation due to the bits and the bit wear in the rotary percussion type of machines results from the feed force, torque and mechanism of rock cutting. Cutting action of the bit, large feed force, large torque results in less bit wear and good chips. On contrary, grinding of the bit, lesser feed and minimum torque results in fine grinding and high bit wear [5]. Driving of bits in the rock affects the drilling economy involved in mining costs, the retainment of sharpened shapes of a bit after blunting and the overall life of the bits. The drill bit impregnated with buttons undergoes outdated service within its estimated life or exceeding it. The reasons are either blunting of bit due to progressive wear-out or complete removal of it at the process of drilling.

2. Previous correlation studies for penetration rate

2.1 Correlation study in percussive drilling

Most of the researchers such as Paone et al [6], Selim and Bruce [7], Kahraman et al [8] developed correlations in percussive drills with the compressive strength of rocks. Fish [9], Bilgin and Kahraman [9,10] developed correlation study for penetration rate in rotary drills with compressive strength. UCS is the most important geophysical properties of rock in all types of drilling machines. Selim and Bruce [7] and Schmidt [11] investigated percussive drilling machine correlating other geomechanical parameters such as tensile strength, shore hardness [12], density, static and dynamic Young's modulus, shear modulus. In addition to above parameters, Selim and Bruce [7] correlated with the coefficient of rock strength(CRS) and percentage of quartz content whereas Schmidt [11] correlated with longitudinal wave velocity, shear wave velocity and Poisson's ratio. Pathinkar and Misra [12] associated with other properties such as specific energy and Mohs Hardness. Kahraman et al. [8] investigated penetration rate in percussive blast hole drills with the Brazilian tensile strength, the point load strength and Schmidt hammer value resulting in strong correlation, the impact strength establishing a good relationship, and, elastic modulus and density with little correlation. Huang and Wang [13] had evaluated a performance assessment of diamond drill bit of diameter 2.375 inches concerning the graphical relationship between the UCS and penetration rate. The bit performance assessed regarding penetration rate, applied torque, and specific energy.

2.2 Correlation studies in rotary drills

Karpuz et al.[14] developed curvilinear regression models for the prediction of penetration rates of rotary blasthole drills, and UCS as the most dominant rock property. Selmer-Olsen and Blindheim [15] performed percussion drilling tests and correlated penetration rates with drilling rate index (DRI). Adamson [16] showed a correlation between rock texture, the texture coefficient and penetration rate of the rotary drilling machine. Howarth et al. [17] correlated penetration rate with various rock properties and found a high correlation with bulk density, saturated compressive strength, apparent porosity and saturated P-wave velocity and good relation with Schmidt hammer value and dry compressive strength. Howarth and Rowland [18] found close relationships between the penetration rate and texture coefficient in percussion drill. Bilgin and Kahraman [10] conducted penetration rate study in rotary drills with the other rock characteristics derived from laboratory tests such as point load strength, Schmidt hammer value, Cerchar hardness, and impact rock strength having the strong correlation, whereas Brazilian tensile strength and cone indenter hardness had relatively manageable relationships. Fish [9] developed a model for rotary drilling in which the Penetration rate is inversely proportional to the strength of the rock. Kahraman et al. [19] developed a mathematical penetration rate model for rotary drills using the drillability index and concluded significant correlations with rock parameters such as compressive strength, tensile strength, point load index, Schmidt hammer value, impact strength, P-wave velocity, elastic modulus and density. Drillability index utilized in the determination of the penetration rate of the drills by conducting the indentation tests of bit-teeth of spherical and conical bits. Kahraman and Bilgin [20] correlated the penetration rate and drillability index of rotary blasthole drills for the conical and spherical bit-tooth. Saeidi et al.[21] monitored the bit wear rate of the Tricone roller bits of rotary drilling machine used in opencast copper mines. He obtained digital images of bits from CCD camera by three techniques in MATLAB and the graphical relations between the normalized cone matrix wear, diametrical wear and weight loss of the bit with the entropy. Saeidi (2) et al. [22] produced a stochastic model for the determining the penetration rate of the rotary drills by considering the UCS, weight on the bit, rotational speed, joint spacing and joint dip. Kahraman [23] investigated the relations between the penetration rates and three different brittleness obtained from compressive strength, tensile strength and percentage of fines for rotary and percussion drills. Kahraman [24] performed correlation study of penetration rate with the compressive strength of the rock as the geomechanical parameter in drilling. Apart from the above study, extensive parametrical study conducted on rotary, down-the-hole and top hammer drills were analyzed combinedly. Rotary drills correlated with the weight on bit, rotational speed, and bit diameter. Down-the-hole hammer dependent on the operating pressure, piston diameter and Schmidt hammer value. Hydraulic top-hammer drills associated with blow frequency and quartz content. Kahraman [25] developed relations between penetration rate and modulus ratio in rotary and percussive drilling machines.

This study focuses on the interdependent function between the wear rate and the penetration rate of the bit of rotary-percussion drill. Previous research studies conducted on penetration rate of the percussion and rotary drill machines was on correlation with other geomechanical and machinery parameters, which play a significant role while performing drilling operation. UCS of the rock is the function of the machinery production, drillability, and life. The life of drilling machine centered at the performance of cutting bits and thrust-down pressure. It reveals the parametrical study of drilling machine by the observations of specific factors in the field and developing an efficient correlation to derive influence of UCS of rock on penetration rate of drills and wear-out rate of the bit while performing drilling operations in opencast mines. The objective of the research is to ascertain mechanical approach for utilization of drilling energy in cutting of rock mass of particular UCS and its effect on operation of drilling bit during the process of drilling. Drilling bit often undergoes wear and tear which affects the penetration rate in a major way.

This research assesses to establish the relations between the penetration rate of the drill and the wear-out rate of the bit. It fulfills the dependence of factor mentioned above in the mining industry to attain the productivity while the drill bit yields on or after its estimated life, thereby decreasing the mining costs in the sectionalized work connected with drilling. The industrial bureaucrats are seeking for different experiments and tests in the laboratory, workshop, and field, increasing the bit wear life with the progressive drill run. The drill bit utilized for cutting travelling longer drilling distance between the continuous grinding and sharpening operations. A particular group of bits chosen to run in a normal trend of a cycle of drilling operation which is managed to continue in a shift-wise pattern from the stage of minimal blunt to sharpening or regrinding. Therefore, this study was extended with a graphical solution and assuring the industrial firms to have a reliable process while undertaking their operations to commence the drilling projects in mining sectors.

3. Field investigation

The opencast mines of Kusunda-Godhur colliery under the Coal India Limited subsidiary, BCCL selected for an investigative scientific study of rotary-percussive drills in five different benches of overburden. The drill rod used varies with the equal lengths of 3m, 4m, and 6m. The diameter of drill bit hammer is of 165 mm connected with a bit having round buttons with a flat face for hammering, which owes drilling capacity of 5000 m in soft rocks to 4000m in hard rocks. Tables 1 and 2 tabulate the data regarding hammer and bit specifications.

TABLE 1: HAMMER SPECIFICATION

Weight (kg)	97
Bit diameter (mm)	148
Hammer length (mm)	1100
Hammer length with bit	1192
Air consumption (cfm)	490-750 (250 psi-350 psi)
Air consumption (m^3/min)	14-21 (18 bar-24 bar)

TABLE 2: BIT SPECIFICATION

Diameter (in mm)	165 mm
Air holes	2
Gauge button	10
Button diameter (gauge)	19 mm
Weight	22 kg

4. Research methodology

4.1 Determination of the penetration rate

The penetration rate of the rotary percussive blasthole drill is carried out from the field investigations in the opencast mines. In this procedure, time study of the drilling includes starting and end time of drilling and their difference calculated as time duration (TD). Time duration (TD) taken by the drill rod to drill a hole, recorded by digital stopwatch in minutes and seconds. Time study of the sandstone bench was conducted and tabulated in Table 3 with careful consideration of units. P. rate is the penetration rate in cm/s and later on converted to mm/s for the convenience in plotting graphical scale. Similarly, it is carried in every bench to assess the penetration rate of the drilling machine and obtaining the tabulated values.

4.2 Determination of the UCS of rock

The UCS of the rock determined from the L-type Schmidt hammer in the field investigation. Blastholes for the Schmidt Hammer readings in each bench were selected. Rock fragments formed from the cutting and drilling removed from the collar of the drill holes and an area within an area of 20cm

TABLE 3: TIME STUDY IN BENCH (SANDSTONE)

Hole no.	Rod no.	(TD) in min and seconds		Total TD (in sec)	Depth of hole (D)	Total depth (cm)	P. rate (in mm/s)
1	1	3	25		6		
	2	1	59	324	2.5	850	26.23
2	1	4	13		6		
	2	3	7	440	2.5	850	19.31
3	1	4	22		6		
	2	2	6	388	2.5	850	21.90
4	1	4	10		6		
	2	1	51	361	2.5	850	23.54
5	1	3	43		6		
	2	2	27	370	2.5	850	22.97

TABLE 4: SCHMIDT HAMMER READING

Hole no.	Rebound reading									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
1	22	32	28	42	26	27	21	16	27	16
2	20	36	34	26	34	21	32	32	32	34
3	27	28	27	29	30	27	31	27	24	29
4	39	27	24	20	26	33	25	41	40	34
5	44	36	36	37	38	22	38	33	30	33

by 20cm of the drill holes nominated for rebound tests. A series of ten rebound tests conducted with the Schmidt hammer for each hole in the bench in the area demarcated before, and these readings recorded as R1 to R10 and paged down in Table 4.

The mean value of ten observations of the Schmidt hammer calculated the average Schmidt rebound number at that point. UCS determined from the table containing Schmidt rebound number and cubical compressive strength (N/mm^2) which was available along with the Schmidt Hammer. Table 5 shows the correlation values between the Average rebound number of the holes and its respective value of UCS, in association with the standard table available along with the Schmidt Hammer.

The variation of the penetration rate with UCS of the rock for different mines was studied. Table 6 shows the average UCS and the average Penetration rate was calculated from the observations near the holes. Average UCS and average penetration rate obtained in table considered for graphical representation of rock material and machine.

4.3 DETERMINATION OF WEAR-OUT RATE OF THE BIT

The wear-out rate was determined from the digitization of images of button bits at the start and end of the drilling operation on that day. The picture analysis property of Fragalyst 4.2 software used in the digitizing the photographic images of the bit. Many buttons embedded on the surface of the bit counted as fragments during digital comparison of the area, shape, and size of each button. A total number of fragmental buttons in each drill bit image results obtained to be equal to the number of buttons and counted to a figure of 20. The difference between the areas as mentioned above indicates flattening of the bit. The researcher observed that the diameter of the bit in "After-drilling" phase is greater than the "Before-drilling" which signifies wear of the buttons in the bit. Table 7 has the numerical figures of the area of a bit in the phases of drilling.

Table 8 explains the wear-out rate derivation from the area of the bit eroded while drilling. The difference between two area divided with the total distance of the bit drilled in the rock in that shift, which evaluates out the wear out rate of the bit. The sandstone specimen in the bench-4 drilled with a distance of 42.5 m and the wear-out area is 36.637 mm^2. The wear-out rate of the bit is (36.637/ 42.5) = 0.862 mm^2/m of the hole drilled. Figs.1 and 2 show the

TABLE 5: UCS AND SCHMIDT HAMMER READING

Hole no.	Avg. rebound reading	UCS (N/mm^2)
1	25.8	26.5
2	30.1	32.9
3	25.4	25
4	30.9	34.4
5	34.7	41.1

TABLE 6: UCS AND PENETRATION RATE FOR EACH BLAST HOLE

UCS (N/mm^2)	Penetration rate (in mm/s)	Avg. UCS (N/mm^2)	Avg. penetration rate (mm/s)
26.5	26		
32.9	19		
25	22	31.98	22.8
34.4	24		
41.1	23		

TABLE 7: AREA OF BIT DRILLED IN DIFFERENT BENCHES

Bench no.	Bench	Area of bit (before)	Area of bit (after)	Difference of area
1	Sandstone	206.95	287.3469	80.3969
2	Shale	109.138	136.258	27.12
3	Shale	126.374	153.091	26.717
4	Sandstone	202.103	238.74	36.637

TABLE 8: EVALUATION OF WEAR-OUT RATE OF THE BIT IN DIFFERENT BENCHES

Bench no.	Bench rock type	Distance in overburden (m)	Wear-out rate (mm^2/m)
1	Sandstone	76.5	1.050
2	Shale	80	0.339
3	Shale	72	0.371
4	Sandstone	42.5	0.862

TABLE 9: UCS AND PENETRATION RATE OF DIFFERENT BENCHES

Bench no.	UCS (N/mm^2)	Penetration rate (mm/s)	Bench rock type
Bench 1	42.46	17	Sandstone
Bench 2	28.6	30	Shale
Bench 3	27.5	28	Shale
Bench 4	31.98	23	Sandstone
Bench 5	35.72	14	Sandstone

superimpose and boundary view of the button bits considered "Before drilling" whereas Figs.3 and 4 show respective above forms of images "After drilling."

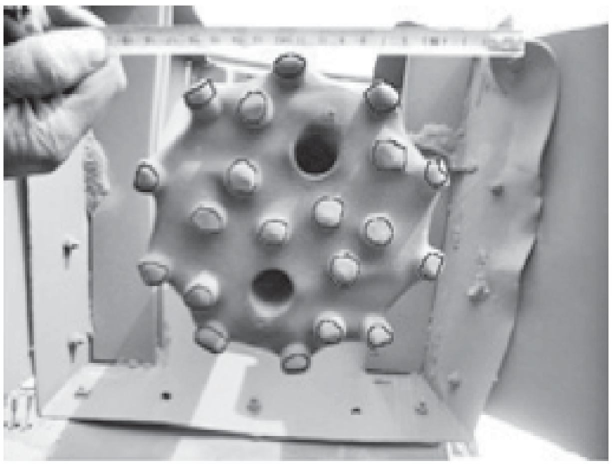

Fig.2 Boundary view (before drilling)

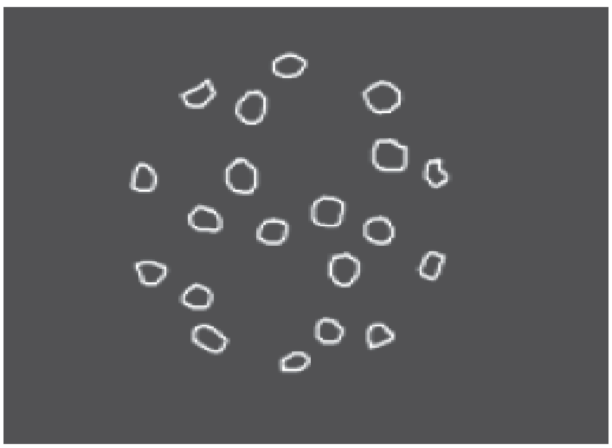

Fig.1 Superimpose view (before drilling)

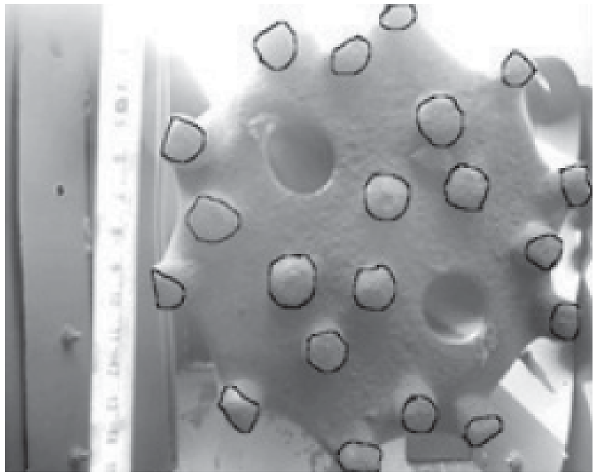

Fig.3 Superimpose view (after drilling)

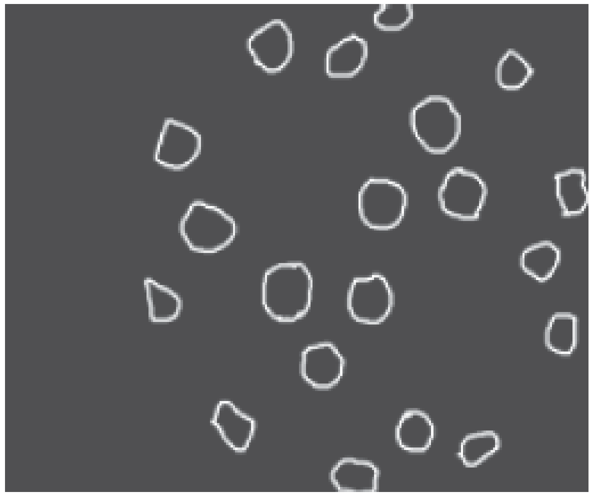

Fig.4 Boundary view (after drilling)

5. Results

5.1. RELATIONSHIP BETWEEN PENETRATION RATE AND UCS

Penetration rate decreases with the increase in UCS of the rock. The rocks were stronger in compression and resist the load due to the drill bit enabled for cutting of the rock. It is because, in harder rock, drill machine will require more energy to drill. The relations between the penetration rate and UCS illustrated in Table 9 and Fig.5.

Rock strength is the ability of the rock to prevent deformation due to the radial and tangential forces of the bit on the rock interface at the circumference periphery and bottom of the drill hole. In this case, the same machine was used in different UCS therefore, penetration rate decreases as the UCS of rock increases at various benches. UCS is an independent physical variable of the rock, and the Penetration rate of the drilling machine in the rock is the dependent variable. As the rock characteristic changes, the penetration rate of the drilling machine also changes according to it. In Fig.5, the regression analysis shows a nearly good fit between the UCS and penetration rate.

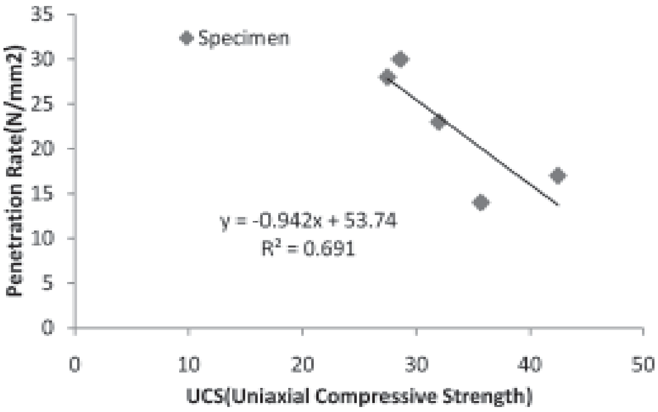

Fig.5 UCS vs penetration rate

5.2 Relationship between Wear-Out Rate and UCS

Table 10 shows UCS of the rock and wear-out rate (in mm^2/meter of the drilled hole) of the bit in the different specimen with the depth of the hole drilled. The UCS values of rock obtained from different bench compared to the corresponding wear-out rate of the bit in that bench. The wear-out rate of a bit in that particular overburden bench increases with the corresponding value of UCS of the rock in a linear trend. Graphical relationship between the values representing the UCS and wear-out rate is shown in Fig.6. UCS of the rock is an independent parameter on which wear-out rate of the bit of a particular specimen is dependent. At the same depth, a drilling machine having constant input energy for drilling should have increased wear-out rate with the increase in UCS of the rock. The grains texture and

Table 10: UCS and wear-out rate of the bit in different benches

Bench no.	Bench	UCS (N/mm^2)	Wear-out rate (mm^2/metre of drilling)	Distance in overburden (m)
Bench-1	Sandstone	42.46	1.05	76.5
Bench-2	Shale	28.6	0.339	80
Bench-3	Shale	27.5	0.371	72
Bench-4	Sandstone	31.98	0.862	42.5

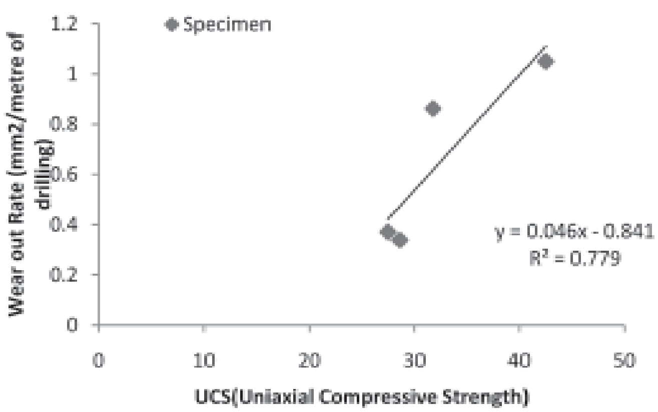

Fig.6 UCS vs. wear-out rate

abrasiveness vary within the different rocks, so the wear-out rate varies in different overburden benches and also differs at various points on the same bench of the rock. Fig.6 shows the curve which resembles that the correlation coefficient R2 is fairly good to describe the parametrical relations of the factors mentioned below.

5.3 Relationship between the penetration rate and wear-out rate

Table 11 shows penetration rate and wear-out rate (in mm^2/meter of the drilled hole) of the bit in the different specimen. There is an increase of the wear-out rate of the bit from Specimen 1 (17, 1.05), Specimen 4 (23, 0.862), Specimen 3 (28, 0.371) and Specimen 4 (23, 0.339) with a decrease of the penetration rate of the bench. Larger the depth of holes leads

Table 11: Penetration rate and wear-out rate of the bit in different benches

Bench no.	Bench	Penetration rate (mm/s)	Wear-out rate (mm^2/m)
Bench 1	Sandstone	17	1.05
Bench 2	Shale	30	0.339
Bench 3	Shale	28	0.371
Bench 4	Sandstone	23	0.862

to more extensive wear-out area of the bit. Therefore, the penetration rate of the drilling machine is larger. Fig.7 reveals the graphical relationship between values representing the penetration rrate and wear-out rate. At larger depths and greater UCS of the rock, the penetration rate of drilling machines decreases. Also, at the same depth, the same machine has a more wear-out rate in harder that reduces the performance of the drill bit. In Fig.7, the parameters satisfies the regression curves with higher values of correlation coefficient of 0.9411, which is a very good fit of the curve obtained in the parametrical study.

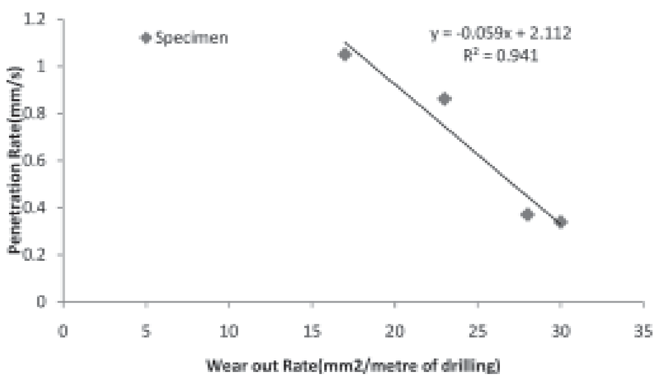

Fig.7 Penetration rate vs. wear-out rate

6. Conclusions

The following conclusions are drawn from the study:

- As the uniaxial compressive strength increases from 27.5 to 42.46 N/mm^2 the penetration rate decreasing from 30 to 14 mm/s while wear-out rate of a bit (in mm^2/meter of the hole drilled) increasing from 0.339 to 1.05. The UCS of the rock is the factor which plays a major role in bit wear of the bit.

- Penetration rate decreases with the increase in the uniaxial compressive strength of the rock. The cutting of the rocks involves the increase in breaking the bonds between the grains of rock which requires drilling energy.
- Penetration rate decreases with the increase of the wear-out rate of the bit.
- Penetration rate and wear-out rate are the two parameters which are dependent on each other, while drilling of the bit performs the cutting mechanism. The resistance of the rock on the drill bit at the bit-rock interface results in the wear-out of the bit. Therefore, complete blunting of the buttons should be within the life of the buttons to enhance the drilling activity and mining economy.

Acknowledgements

The authors express their gratitude to management of BCCL for cooperation in carrying out field study.

References

1. Australian Drilling Industry Training Committee Limited (1997): Geology for Drillers. Drilling – The Manual of Methods, Applications and Management, CRC Press, pp.163-196.
2. Gokhale, B. V.: "Blasthole drilling technology. Theoretical aspects in drilling." *Multifields*, pp. 247-276.
3. Yarali, O. and Soyer, E. (2013): "Assessment of relationships between drilling rate index and mechanical properties of rocks," *Tunnelling and Underground Space Technology*, 33 :46-53.
4. Jimeno, E. L., Jimeno, C. L. and Carcedo, F. J. A. (1995): Rotary Percussive Drilling.Drilling and Blasting of Rocks. Taylor & Francis, New York, pp.10-35
5. Australian Drilling Industry Training Committee Limited (1997): Drilling Operations. Drilling – The Manual of Methods, Applications and Management, CRC Press, pp.243-314.
6. Paone, J., Madson, D. and Bruce, W. E. (1969): "Drillability Studies – Laboratory Percussive Drilling," *US Bureau of Mines RI 7300*.
7. Selim, A. A. and Bruce, W. E. (1970): "Prediction of Penetration Rate for Percussive Drilling," *US Bureau of Mines RI 7396*.
8. Kahraman, S., Bilgin, N. and Feridunoglu, C. (2003): "Dominant rock properties affecting penetration rate of percussive drills." *Int. J. Rock Mech. Min. Sci.* 40(5),711-723.
9. Fish, B. G. (1968): "The basic variables in rotary drilling." *Mine & Quarry Engineering* (1968); 27:74-81.
10. Bilgin, N. and Kahraman, S. (2003): Drillability prediction in rotary blasthole drilling. In: Proc. 18th Int. Mining Cong. And Exhibition of Turkey, Antalya, Turkey, pp.177-182.
11. Schmidt, R. L. (1972): Drillability Studies – Percussive drilling in the field.
12. Pathinkar, A. G. and Misra, G. B. (1980): "Drillability of rocks in percussive drilling from 'energy per unit volume as determined with a microbit." *Min Eng.* 32, 1407-1410.
13. Huang, S. L. and Wang, S. W. (1997): "The Mechanics of Diamond core drilling of rocks," *Int. J. Rock Mech. & Min. Sci.*, 34, 3-4, paper No.134.
14. Karpuz, C., Pasamehmetoglu, A. G., Dincer, T. and Muftuoglu, Y. (1990): Drillability studies on the rotary blast hole drilling of lignite overburden series.
15. Selmer-Olsen, R. and Blindheim, O. T. (1970): On thedrillability of rock by percussive drilling. In: proc. 2nd Congress Int. Soc. Rock Mech., pp 65-70.
16. Adamson, W. R. (1984): Correlation of Model Excavating Machine Performance with Rock Properties and Rotary Drilling Performance Data. MSc, Thesis, Univ. of Queensland,.
17. Howarth, D. F., Adamson, W. R. and Brendt, J. R. (1986): "Correlation of model tunnel boring and drilling machine performances with rock properties." *Int. J. Rock Mech. Min. Sci.* 23,171-175.
18. Howarth, D. F. and Rowland, J. C. (1987): "Quantitative assessment of rock texture and correlation with drillability and strength properties." *Rock Mech. Rock Eng.* 20, 57-85.
19. Kahraman, S., Balci, C., Yazici, S. and Bilgin, N. (2000): "Prediction of the penetration rate of the rotary blasthole drills using a new drillability index." *Int. J. Rock Mech. Min. Recl.* 4, 89-93.
20. Kahraman, S. and Bilgin, N. (2007): Performance prediction of rotary blast hole drills from load-indentation curves. In: 5th Int. Conference Mining Techniques, Krynica, Poland, pp.11-17.
21. Saeidi, O., Rostami, J., Ataei, M. and Torabi S. R. (2014): "Use of digital image processing techniques for evaluating wear of cemented carbide bits in rotary drilling," *Automation in Construction* 44: 140-151.
22. Saeidi, O., Torabi, S. R., Ataei, M. and Rostami, J. (2014): "A stochastic penetration rate model for rotary drilling in surface mines." *International Journal of Rock Mechanics & Mining Sciences*, 68: 55-65.
23. Kahraman, S. (2002): "Correlation of TBM and drilling performances with rock brittleness." *Eng. Geol.* 65, 269-283.
24. Kahraman, S. (1999): "Rotary and percussive drilling prediction using regression analysis." *Int. J. Rock Mech. Min. Sci.* 36, 981-989
25. Kahraman , S. (2003): "Performance analysis of drilling machines using rock modulus ratio." *J. S. Afr. Inst. Min. Metall.*, 103, 515-522.