B.S. CHOUDHARY
and
ASFAR MOBIN KHAN

Roadheader performance during development of a coal drive

Drilling and blasting is the most widely used excavation method in mining and tunnelling especially in hard rock conditions. But in recent years, the application of mechanical excavators in hard rock, especially in fractured geological formations has increased considerably. Mechanical excavation is very attractive for many project because of their techno-economic advantages including improved safety, ease from automation, finished and undamaged excavation dimension, almost nil ground vibration, etc. Under mechanical excavation roadheaders can be a good option. It is a versatile excavation machines favoured in mining operation due to a high degree of mobility, flexible cutting profile, selective mining, providing immediate access to the face and the capability to cut medium strengths rocks. It is also seen performing in high strength rock but only in case of moderately jointed rocks. Performance analysis of roadheader in soft rock drivages is an important task. This can be determined by studying various performance tests or models and carrying out actual underground cutting. With this respect, a data-base was established from detailed field data including the measured instantaneous cutting rates (ICR) and geo-mechanical parameters (uniaxial compressive strength) of the coal measure rocks for each cutting condition in the tunnels. In this paper the study was conducted at two different coal mines to analyse the performance of roadheader vis-à-vis performance predicted by one model. It was found that the roadheaders are working below the predicted performance in development drive of coal mine.

Keywords: Roadheader, coal drive, rock strength, performance, rock cutting

I. Introduction

Roadheader offer a unique capability and flexibility for the excavation of soft to medium strength rock formations, hence, are extensively used in underground mining and tunnelling operations. A critical issue in successful roadheader application is the ability to evaluate and predict the machine performance. Roadheader were first developed for mechanical excavation of coal in the early 1950s. Today their application areas have expanded beyond coal mining as a result of continual performance increases brought about by new technological developments and design improvements. The major improvements achieved in the last 50 years consist of: steadily increasing machine weight, size, and cutter head power, improved design of boom, muck pick-up and loading systems, more efficient cutter head design, metallurgical developments in cutting bits, advances in hydraulic and electrical systems, and more widespread use of automation and remote control features. All these have led to drastic enhancements in machine cutting capabilities, system availability and service life. Roadheaders are the most widely used underground partial-face excavation machines for soft to medium strength rocks, particularly sedimentary rocks as shown in Fig.1. They are used for both development and production. The machines can be divided into three categories, Light (weight up to 35 tonne), medium (weight up to 55 tonne) and heavy (weight up to 55 tonne) [1]. In the mines light roadheaders are most popular. Many researchers investigated the factors affecting the performance of roadheaders and impact hammers. It is believed that new published data will improve existing performance prediction models [2, 3, 4]. Use of Roadheader in underground metalliferous mining is still untouched area which can be explored for future applicability of roadheader.

Fig.1 Transverse/ripper type roadheader (Alpine Miner)

Mr. B.S. Choudhary, Assistant Professor, Email:bhanwar_ism@hotmail.com and Mr. Asfar Mobin Khan, M.Tech. (TUST) Student, Email: asfarsuri86@gmail.com, Department of Mining Engineering, Indian School of Mines, Dhanbad 826004

The performance analysis of roadheader is a very important task to improve the efficiency. Many researchers have given their model to analyze the performance based on their study. Some of them are:

Barendsen [5] investigated the difference in efficiency of machines working on a cutting principle and machine which crush the rock to powder and, as shown in Fig.2, predicts the performance for both cutting systems. Barendsen uses the specific energy used by the machine in excavating a unit volume of rock as the productivity indicator.

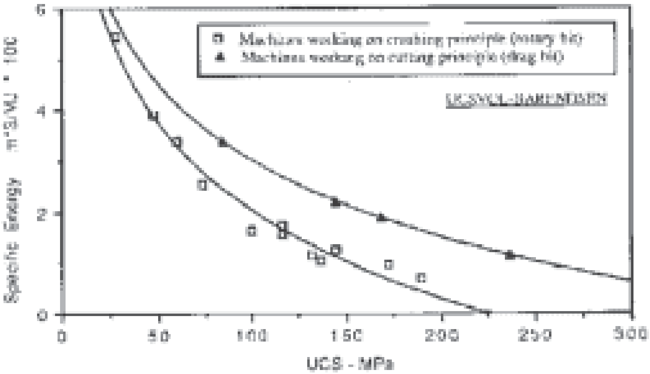

Fig.2 Uniaxial compressive strength vs specific energy used by the machine [5]

Poole and Farmer [6] in their study found that Schmidt hammer gave a better correlation ($r = 0.7$) with penetration rates of Dosco MK2A roadheader in English coal measure strata. Farmer et al [7] stated that for a given power of roadheader, excavtion rate in solid bank m^3/cutting hour might be predicted using specific energy value as $SE = \sigma_c^2/2E$.

Bilgin et al [8] suggested that the machine advance rate of roadheader can be estimated using UCS and RQD. They recommended that the Rock Mass Cuttability Index (RMCI) can be defined as:

$$RQD = 115\text{-}3.3\ J_v \qquad \text{... ... (1)}$$

$$RMCI = \sigma_c \left\{ \frac{RQD^{2/3}}{100} \right\} \qquad \text{... ... (2)}$$

Where, RQD = rock quality designation, (%); J_v = total number of discontinuities per cubic meter; RMCI = Rock Mass Cuttability Index, kg/cm^2; σ_c = UCS, kg/cm^2

Gehring [9] predicted the performance of a rock cutting machine such as a roadheader and suggested the following equation:

$$L = \frac{k}{\sigma c} N \qquad \text{... ... (3)}$$

Where, L = cutting performance, b cm/h/; σ_c = UCS, MPa; N = cutter head power, kW.

K = a factor for consideration of relatively cuttability of a rock with certain UCS and for consideration of tuning effect between roadheader and rock.

To study the relationship between ICR and rock uniaxial compressive strength (UCS) for a milling type roadheader with 230kW cutter head power and an Alpine Miner AM 100 ripping type roadheader with 250kW cutter head power. He developed following equations:

$$ICR = 719/(UCS)^{0.78} \text{ ... ... for ripping type roadheaders} \qquad \text{... ... (4)}$$

$$ICR = 1739/(UCS)^{1.13} \text{ ... ... for milling type roadheaders} \qquad \text{... ... (5)}$$

Where, ICR denotes as cutting performance (m^3/hr); and UCS as the uniaxial compressive strength (MPa)

Bilgin[10] showed that main factors governing performance of roadheader were rock compressive strength and RQD. He suggested that the instantaneous cutting rate could be best predicted from rock mass cuttability index as:

$$RMCI = \sigma_c \left\{ \frac{RQD^{2/3}}{100} \right\} \qquad \text{... ... (6)}$$

Where, RMCI = Rock Mass Cuttability Index(kg/cm$^{2)}$; RQD = rock quality designation (%); σ_c = UCS, kg/cm^2

He also suggested to calculate the ICR using the RMCI values for roadheader having cutting power of 95 hp

$$ICR = 0.28\ P(0.974)^{RMCI} \qquad \text{... ... (7)}$$

Where, P is the power of cutting head (hp); RMCI is the rock mass cuttability

Fowell and Johnson [11] suggested that the instrumented cutting test using a full scale drag tool has been found to be a valuable test for identifying problems associated with rock excavation with drag picks.

Ozdemir and Rostami [12] stated a realistic method to predict the cutting rate of any excavation machine in massive rock formation was reported to use cutting power, optimum specific energy and energy transfer ratio.

$$ICR = K \left\{ \frac{p}{SE_{opt}} \right\} \qquad \text{... ... (8)}$$

Where, K= energy transfer ratio from cutting head to rock formation; P = cutting power of cutting head in kW; SE_{opt} = optimum specific energy in kWh/m^3

Rostemi and Ozdemir ponted out that K changes from 0.4 for roadheader to 0.9 for TBM.

Rostami et al [13] pointed out that the roadheader production rate and pick consumption are controlled by several parameters including: rock parameters, such as rock compressive and tensile strength, etc., ground conditions, such as degree of jointing (RQD), joint conditions, ground water, etc., machine specification, including machine weight, cutter head power, sumping, arcing lifting, and lowering forces, cutter head type (axial or transverse), bit type, size, number and allocation of bits on the cutter head, the capacity of backup system, and other characteristics, operational parameters, such as shape, size, and length of opening, inclination, quality of labour, etc.

Copur [14,15] stated that if the power and weight of roadheader were considered together, in addition to rock compressive strength, cutting rate prediction were more realistic. The predictive equations for transverse (ripping type) roadheaders are as follows:

$$ICR = 27.511e^{0.0023(RPI)} \quad \text{... ... (9)}$$

$$RPI = P*W/UCS \quad \text{... ... (10)}$$

Where, ICR = Instantaneous cutting rate (m^3/hr or tonnes/hr); RPI (roadheader penetration index); UCS (uniaxial compressive strength MPa); W (roadheader weight in tones); P (power of cutting head kW); and e (base of natural logarithm).

Thuro and Plinninger [16,17,18] determined the relationship between the cutting rate and the uniaxial compressive strength for 132kW roadheader. They found that the correlation between UCS and cutting performance is not sufficient in predicting the cutting rate. They obtained higher correlation by putting the cutting performance against specific destruction work (kJ/m^3). They presented the following predictive equation:

$$ICR = 107.6\text{-}19.5\ln (Wz) \quad \text{... ... (11)}$$

Where, Wz is the cutting performance (m^3/hr) and the specific destruction work (kJ/m^3).

Ebrahimabadi et al [19] predicted the performance of roadheaders based on brittleness index. Pick consumption index (PCI) was introduced as a parameter having a good relation with pick or bit consumption rates (PCR).

$$RMBI = e^{\{UCS/BTS\}} \times \{RQD/100\}^{3} \quad \text{... ... (12)}$$

$$ICR = 30.74\,(RMBI)^{0.23} \quad \text{... ... (13)}$$

$$PCI = e^{RMBI} \times \{UCS/P\} \quad \text{... ... (14)}$$

$$PCR = 45.10\,(PCI)^{-0.15} \quad \text{... ... (15)}$$

Where, RMBI is the rock mass brittleness index; UCS is the uniaxial compressive strength of rock (MPa); BTS is the Brazilian tensile strength of rock (MPa); RQD is the rock quality designation of the rock mass (%); PCI is the pick consumption index; PCR is the pick consumption rate (m^3/pick); and P is the cutter head power (kW).

After evaluating the various models to predict the roadheader cutting performance the model given by [14, 15] was deployed to compare field results and for pointing out the necessary shortcomings.

II. Field study and research methodology

The study was conducted at two different underground coal mines to collect the actual cutting rate of the roadheaders. The mine-A was designed by Polish consultants under a technical collaboration for horizon mining system to produce coking coal from coal seams at depth of 500 meters. The roadheader was deployed in a coal seam development. The dimension of the drive was 2m high, 4.5m wide. The Dosco roadheader was deployed to cut the coal. The major specifications of the machine are; motor capacity of 75 kW (2 nos.), weight of the machine was 20 tonnes, pics (96 nos.) was made of tungsten carbide. In mine-B the roadheader was deployed to develop coal seam at the depth of 350m. The dimension of the drive was 2.8m high, 4.2m wide. The major specifications of the machine are; motor capacity of 110 kW (2 nos.), weight of the machine was 24 tonnes, pics was made of tungsten carbide, speed of cutter motor was 470rpm; output speed of cutter transmission was 88.7 rpm; output torque of cutter transmission was 10769 Nm; working pressure was 200 bar. Densities of coal at both the mines are 1350kg/m^3 and 1300kg/m^3 respectively for mine A and for mine B. The Schmidt hammer was used to find the compressive strength of the rock at both the mines during recording the cutting rate of the roadheader. The Schmidt hammer rebound hardness test is a simple and non-destructive test originally developed in 1948 for a quick measurement of UCS and later was extended to estimate the hardness and strength of rock [20]. The compressive strength of the rock was determined at interval of 2m in horizontal direction of both the side of the wall of the drive to get the rebound value after cutting the coal. Among the numbers obtained, the mean value was considered as the Schmidt number. This procedure of performing Schmidt test was a compromise to the ISRM suggested method [21] where 10 higher numbers were selected from 20 tests in the selected area. Schmidt hammer rebound number and respective converted uniaxial compressive strength values are given in Tables 1 and 2.

2.1 SCHMIDT REBOUND HAMMER

The Schmidt Hammer consists of a spring-loaded piston which is released when the plunger is pressed against a surface. The impact of the piston onto the plunger transfers the energy to the material. The extent to which this energy is recovered depends on the hardness (or impact penetration/damage resistance) of the material, which is expressed as a percentage of the maximum stretched length of the key spring before the release of the piston to its length after the rebound.

The impact energy of the SH determines its range of applicability. Accordingly, this limitation should be kept in mind in selecting the hammer type. For instance, the standard L- and N-type hammers, with respective impact energies of 0.735 and 2.207 Nm.

The N-type (Fig.3) hammer is less sensitive to surface irregularities, and should be preferred in field applications; while the L-type hammer has greater sensitivity in the lower range and gives better results when testing weak, porous and weathered rocks.

Table 1: Details of the field observation at mine-A

Days		D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	D-10
Cutting drive area (m^2)		9	9	9	9	9	9	9	9	9	9
Advancement (m/hr)		1.54	2.32	1.52	1.425	1.23	1.56	2.23	1.26	1.96	1.82
Avg. Schmidt Hammer rebound number		29	24	33	34	41	28	26	38	26	28
UCS (MPa)		21.56	15.68	29.4	30.38	42.14	20.58	17.64	37.24	17.64	20.58
Power (kW)		75	75	75	75	75	75	75	75	75	75
ICR(m3/hr)		13.86	20.90	13.68	12.83	11.07	14.04	20.07	11.34	17.64	16.38
ICR (tonnes/hr)		18.71	28.22	18.47	17.31	14.95	18.95	27.09	15.31	23.81	22.11
Copur *et al*	ICR	33.055	34.28	30.92	30.82	29.86	32.51	33.46	30.16	33.46	32.51
	RPI	80.16	95.66	51.02	49.37	35.59	72.88	85.03	40.27	85.03	72.88

Table 2: Details of the field observation at mine-B

Days		D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	D-10
Cutting drive area (m^2)		11.76	11.76	11.76	11.76	11.76	11.76	11.76	11.76	11.76	11.76
Advancement (m/hr)		1.43	2.32	2.09	1.86	1.32	2.33	1.68	2.0	1.6	3.03
Avg. Schmidt Hammer rebound number		32	22	24	26	31	23	28	26	30	21
UCS (MPa)		27.5	11.76	15.7	17.7	25.5	13.7	20.6	17.7	23.5	11.3
Power (kW)		110	110	110	110	110	110	110	110	110	110
ICR(m3/hr)		16.81	27.26	24.63	21.89	15.52	27.42	19.72	23.52	18.76	35.64
ICR (tonnes/hr)		21.86	35.45	32.02	28.46	20.17	35.65	25.64	30.58	24.39	46.34
Copur *et al*	ICR	34.31	46.1	40.5	38.76	34.9	42.85	36.94	38.77	35.61	47.1
	RPI	96	224.45	168.2	149.15	103.5	192.7	128.2	149.2	112.3	233.6

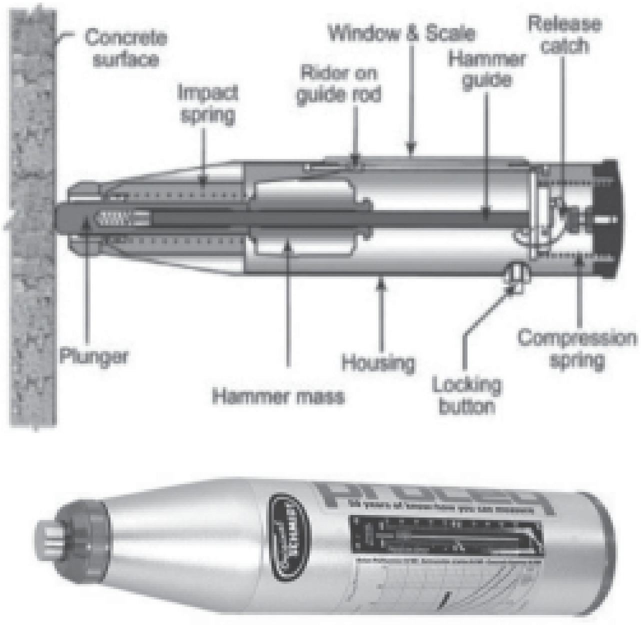

Fig.3 Schmidt rebound hammer (Proceq N type)

Calibration

SH are supplied with calibration anvils with vertically guided impact points made of steel as hard as that of the plunger tip (usually Brinell 500 or Rockwell 52 C). It is essential to verify that the hammers maintain their standard rebound values before and after field investigations. In correlation studies, two consistent readings within the predetermined range of rebound from the anvil should be taken before and after testing each specimen. A drift in the calibrated rebound values may suggest that the key spring is losing its stiffness and should ideally be replaced. If this is not possible, a correction factor (CF) for the hammer should be calculated [1] and applied to all readings to account for the loss of stiffness:

$$CF = \frac{\text{Specified standard value of the anvil}}{\text{Average of ten readings on the anvil}}$$

Data gathering and reduction

For data gathering, 20 rebound values, as recommended by the earlier ISRM suggested method should be recorded from single impacts separated by at least a plunger diameter (to be adjusted according to the extent of impact crater and radial cracks). On the other hand, the test may be stopped when any ten subsequent readings differ only by four (corresponding to SH repeatability range of ±2)

III. Results and discussions

The field observations at mine A&B are tabulated in Tables 1 and 2. The results are plotted graphically and are shown in the Figs. 4, 5 and 6.

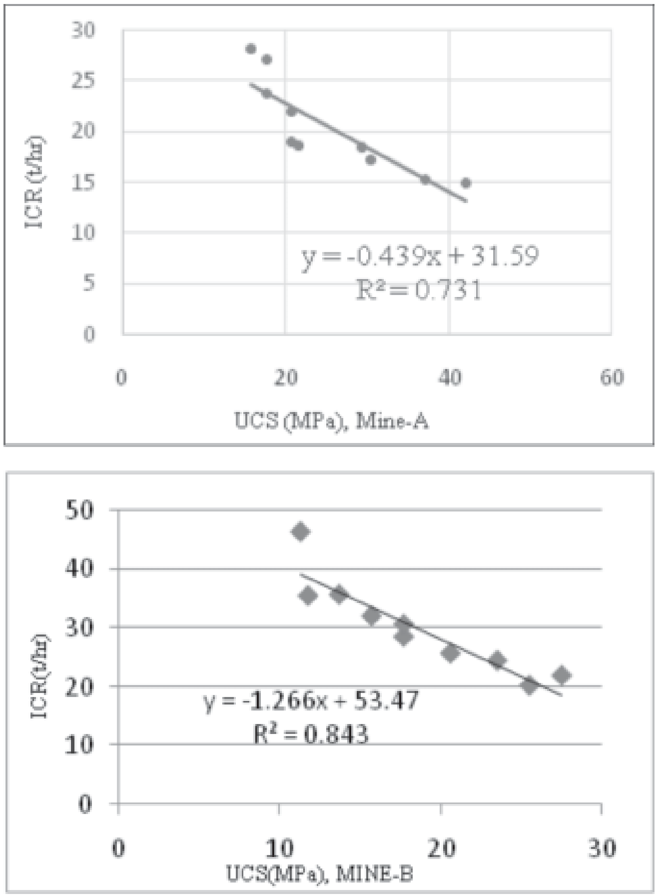

Fig.4 Graph between uniaxial compressive strength (UCS) and instantaneous cutting rate (ICR)

Relationship between uniaxial compressive strength (UCS) and instantaneous cutting rate (ICR)

The relationship between uniaxial compressive strength (UCS) and instantaneous cutting rate (ICR) is derived from the Tables 1 and 2 and shown in Fig.4 for Mine-A and Mine-B.

From the above graphs it can be said that as UCS is increases the value of ICR is reduces and vice versa for both the mines. The reason behind this is that, as the compressive strength increases the machine faces difficulties in cutting the rock. The variability in UCS is mainly due to intercalation of shale, sandstone, carbonaceous shale. The variation in ICR for mine-A is 14.95 to 28.22 (47%) tonnes per hour at UCS

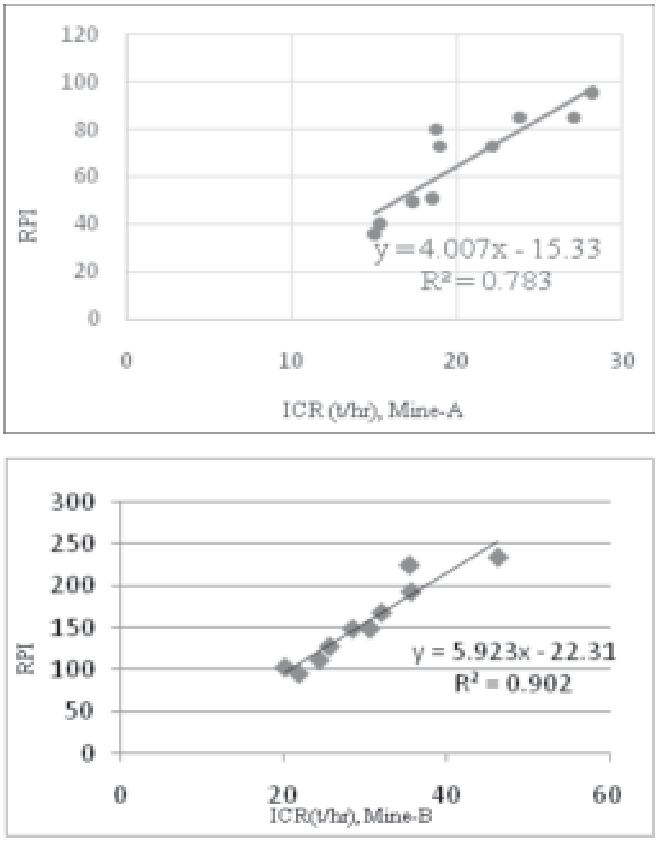

Fig.5 Graph between instantaneous cutting rate (ICR) and roadheader penetration index (RPI)

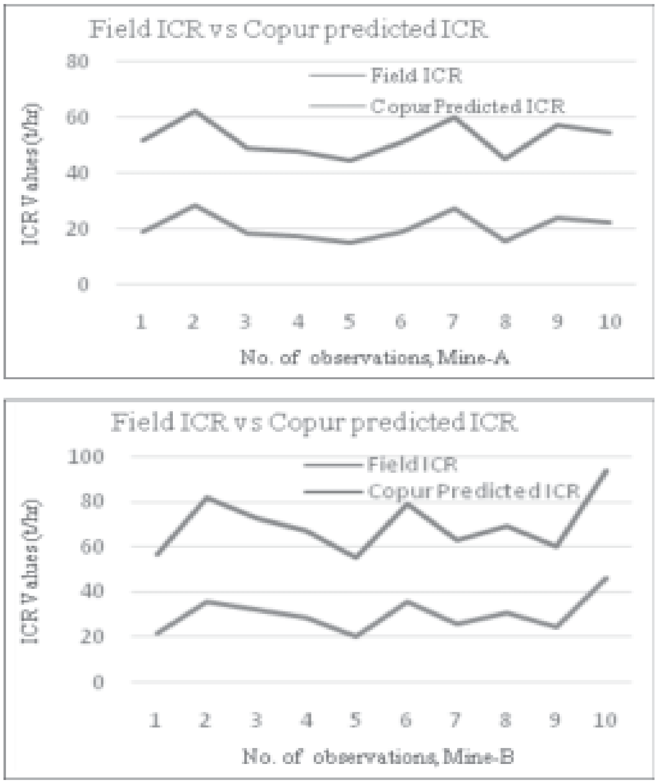

Fig.6 Comparative graph showing the ICR predicted by the Copur model and the actual obtained during field study at mine-A and Mine-B

variation of 42.14 to 15.68 MPa (62.79%) and for mine-B is 20.17 to 46.34 (56.47%) tonnes per hour at UCS variation of 25.5 to 11.3 MPa (55.68%). The ICR variation in mine-A is more due to variation in UCS as well as other factors such as mucking rate, operator efficiency, ground support, gas emissions, ventilation etc.

Relationship between instantaneous cutting rate (ICR) and roadheader penetration index (RPI)

The relationship between instantaneous cutting rate (ICR) and roadheader penetration index (RPI) is derived from the Tables 1 and 2 and shown in Fig.5 for mine-A and Mine-B.

From the above graphs it can be said that as ICR increases the value of RPI is also increases and vice versa for both the mines. The reason behind this is that, as the compressive strength increases the machine cutting rate decreases. The variability in UCS is mainly due to intercalation of shale, sandstone, carbonaceous shale. The same types of results are predicted by Copurs also.

Comparative graph showing the ICR predicted by the Copur model and the actual obtained during field study

Comparative graph showing the ICR predicted by the Copur model and the actual obtained during field study is shown in the Fig.6 for mine-A and mine-B.

In this graph we see that the field ICR values and Copur ICR values differ in all the observations. It means the roadheader performances at both the mines are lower compared to the performance predicted by the Copur model. The reason behind this gap is due to:

- In efficient muck disposal (too much time taken consequently standby time increases)
- Poor workmanship (operators are not trained enough)
- Old machinery
- In sufficient ventilation (excess methane emission), lighting, water availability
- Hydraulic roadheader machine get heated after some time of operation (the hydraulic fluids gets heated up so operation is to be stopped from time to time to maintain the temperature of fluid)
- Poor working condition in the mines which retards the effectiveness of the whole environment.
- Difficulty in installation in supporting system

IV. Conclusions

The study was conducted at two different underground coal mines where transverse type roadheaders were deployed for cutting the coal. During study the rock characterization of cutting face at both mines were done with the help of Schmidt hammer. The cutting performance of the roadheaders were analysed with respect to the Copur's model and the following findings were observed. From the above study the following conclusions may be drawn:

- The variation in ICR and UCS for mine-A is (47%) and (62.79%) respectively while for mine-B is (56.47%) and (55.68%) respectively.
- The main reasons contributing to under performance are inefficient muck disposal (too much time taken consequently standby time increases), poor workmanship (operators are not trained enough), old machinery, insufficient ventilation (excess methane emission), lighting, water availability, hydraulic roadheader machine get heated after some time of operation (the hydraulic fluids gets heated up so operation is to be stopped from time to time to maintain the temperature of fluid), poor working condition in the mines which retards the effectiveness of the whole environment, difficulty in installation in supporting system.

References

[1] Dariusz Jasiulek, Krzysztof Stankiewicz (2011): "An adaptive control system of roadheader with intelligent modelling of mechanical features of mined rock", *Journal of KONES Powertrain and Transport,* Vol. 18, No. 2 .

[2] Bilgin, N., Yazýcý, S., Eskikaya, S. (1996): "A model to predict the performance of roadheaders and impact hammers in tunnel drivages", EUROCK, September 2-5, Torino, pp: 710-721.

[3] Bilgin, N., Kuzu, C., Eskikaya, S., (1997): "Cutting performance of rock hammers and roadheaders in Istanbul Metro drivages". In: Proceedings, Word Tunnel Congress'97, "Tunnels for People", Balkema, pp: 455–460.

[4] Copur, H., Tuncdemir, H., Bilgin, N., Dincer, T (2001): ''Specific energy as a criterion for the use of rapid excavation systems in Turkish mines". The Institution of Mining and Metallurgy. Transactions Section – A Mining Technology 110, November–December, pp: 149–157.

[5] Barendsen P. (1970): Tunnelling with Machines Working on the Undercutting Principle, (Ed) Goodman J. A., "The Technology and Potential of Tunnelling", Proceedings of South African Tunnelling Conference, July, pp. 53 – 58.

[6] Poole, RW, and Farmer, I W. (1980): "Consistency and repeatability of Schmidt hammer rebound data during field testing" (Technical Note) *Int. Journal Rock Mech Mm SeiGeomechAbstr 17,* November, pp: 167-171.

[7] Farmer, I.W., Garrity, P., (1987): "Prediction of roadheader cutting performance from fracture toughness considerations". In: Proceedings of the 6th International Congress on Rock Mechanics, Montreal, Canada, vol. 1, pp. 621–624.

(Continued on page 135)

[22] ZumGahr K.H., (1987): Microstructure and wear of materials, Elsevier, Amsterdam.

[23] Stolarski T.A., (2000): Tribology in machine design, Butterworth–Heinemann, Oxford.

[24] Plis M.N., Wingquist C.F., and Roepke W.W., (1988): “Preliminary Evaluation of the Relationship of Bit Wear to Cutting Distance, Forces and Dust Using Selected Commercial and Experimental Coal and Rock Cutting Tools”. USBM, RI-9193, 63.

[25] Martin J.A., and Fowell R.J., (1997): “Factors governing the onset of severe drag tool wear in rock cutting”, *International Journal of Rock Mechanics and Mining Sciences*, vol. 34, pp. 59-69.

[26] Loui J.P., and Rao Karanam U.M., (2005): “Heat transfer simulation in drag-pick cutting of rocks”, *Tunnelling and underground space technology,* vol. 20, pp. 263-270.

[27] Song-yong L., (2011): “Method to determine installing angle of conical point attack pick”, J. *Cent. South Univ. Technol*., vol. 18, pp. 1994-2000.

[28] MacGregor I.M., Baker R.H., and Luyckx S.B., (1990): “A comparison between the wear of continuous miner button picks and the wear of pointed picks used in South African Collieries”, *Mining sc. and tech,* vol. 11, pp. 213-222.

[29] Beste U., and Jacobson S., (2002): “Friction between a cemented carbide rock drill button and different rock types”, *Wear*, vol. 253, pp. 1219-1221.

[30] Dewangan S., Chattopadhayaya S., and Hloch S., (2015): “Wear assessment of conical pick used in coal cutting operation”, *Rock Mechanics and Rock Engineering,* vol. 48, pp. 2129-2139.

[31] Beste U. and Jacobson S., (2008): “A new view of the deterioration and wear of WC/CO cemented carbide rock drill buttons”, *Wear*, 264, pp. 1129–1141.

[32] Olovsjo S., Johanson R., Falsaû F., Bexell U., and Olsson M., (2013): “Surface failure and wear of cemented carbide rock drill buttons—The importance of sample preparation and optimized microscopy settings”, *Wear*, 302, pp. 1546-1554.

ROADHEADER PERFORMANCE DURING DEVELOPMENT OF A COAL DRIVE

(Continued from page 104)

[8] Bilgin, N., Seyrek, T., Shahriar, K. (1988): “Roadheader performance in Istanbul”, Golden Horn clean-up contributes valuable data. *Tunnels and Tunnelling*, June, pp: 41–44.

[9] Gehring, K. H., (1989): A cutting comparison, *Tunnels & Tunnelling*, pp: 27-30.

[10] Bilgin, N., Seyrek, T., Erdinc, E., Shahriar, K., (1990): Roadheaders glean valuable tips for Istanbul Metro. *Tunnels and Tunnelling*, October, pp: 29–32.

[11] Fowell, R.J. and Johnson, S.T. (1991): “Cuttability Assessment Applied to Drag Tool Tunnelling Machines”, Proc. 7thInt. Congress Rock Mechanics. ISRM ed. Wittke, A.A. Balkema, Achen, pp :985-990.

[12] Rostami, J., Ozdemir, L., Neil, D.M. (1994): Performance prediction: a key issue in mechanical hard rock mining. *Mining Engineering*, pp:1263–1267.

[13] J. Rostami, L. Ozdemir, D.M. Neil (1994): Performance prediction: a key issue in mechanical hard rock mining, *Mining Engineering* (November), pp. 1263–1267.

[14] Copur, H., Ozdemir, L., Rostami, J. (1998): “Roadheader applications in mining and tunnelling industries”, *The Mining Engineer*, March, pp:38-42.

[15] Copur, H., Rostami, J., Ozdemir, L., Bilgin, N. (1997): Studies on performance prediction of roadheaders. In: Proceedings of the 4th International Symposium on Mine Mechanization and Automation, Brisbane, Qld., Australia, pp: A4-1–A4-7.

[16] Thuro, K., Plinninger, R.J. (1998): “Geological limits in roadheader excavation – four case studies”, 8th International IAEG Congress, Balkema, Rotterdam, pp: 21-25.

[17] Thuro, K., Plinninger, R.J. (1999): “Roadheader excavation performance-geological and geotechnical influences”, 9th ISRM Congress Paris, Theme 3: Rock dynamics and tectonophysics/rock cutting and drilling, pp:25-28.

[18] Thuro, K.Plinninger, R.J. (1999): “Predicting roadheader advance rates”. *Tunnels and Tunnelling International*, June, pp: 36–39.

[19] Ebrahimabadi A., Goshtasbi, K. Shahriar, M. CheraghiSeifabad, (2010, 2011): “Predictive Models for Roadheaders Cutting Performance in Coal Measure Rocks”, *Bulletin of the Earth Sciences Application and Research Centre of Hacettepe University*, 32 (2), pp: 89-104.

[20] Torabi, S. R. (2005): “Reliability of the application of Schmidt hammer in determination of the UCS”, Final project report, in Persian, Shahrood University of Technology, and Shahrood, Iran.

[21] Brown, E.T. (1981): ISRM suggested methods – rock characterization, testing and monitoring, Pergamon Press, Oxford.