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*Original Article*

# Modelling the Performance Indicators of Surface Miners in Coal Mines Using Coal Cuttability Factor

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***Abstract*** - *Extraction of rock can be achieved either through drilling and blasting or through mechanical means. The economics of mechanical rock excavation depends on achieved rates of production and the operating cost. Pick and diesel consumption accounts for around 70% of the operating cost of surface miners. Thus, production rate, specific pick, and diesel consumption are considered the key performance indicators of surface miners. The cutting performance of a surface miner varies with respect to rock characteristics. So, assessment of these performance indicators beforehand would help the coal companies in better selection of surface miners for a given rock and production requirement. The study was performed at 10 mines of Mahanadi Coalfields Limited in Odisha, where about 75 surface miners of different make and models are in operation. A coal cuttability factor for coal has been developed using a combination of intact rock, rock mass and machine parameters like Uniaxial Compressive Strength, Laboratory and Insitu P-wave velocity, Power to Weight ratio of the machine. Empirical relations for estimating the key performance indicators using the coal cuttability factor were developed. The correlation coefficient for estimating normalized production rate ($m^3$/hr/m), pick consumption and diesel consumption for cutting 1000$m^3$ of coal and dirt bands was found to be 0.73, 0.82 and 0.77, respectively. The models have been validated with the field data where the % error was found to be within 20%.*

***Keywords*** - *Surface miner, Diesel, Performance, Coal, Modelling.*

## 1. Introduction

Rock is heterogeneous in nature and can be extracted either through drilling and blasting or mechanical ripping or cutting using machinery like ripper-dozer, vertical ripper, rock breakers, surface miners, bucket wheel excavators, continuous miners, shearers, road headers, tunnel boring machines, high wall miners etc. drilling and blasting is the most predominant method being followed for breaking hard rocks and overburden material in coal mines.

Blasting is associated with the risk of misfire, fly rock, ground vibrations, air overpressure, noise, blasting fumes, and formation of boulders, because of which it cannot be used in mines where habitats are in close vicinity. Mechanical cutting technology has evolved over time and is now being applied for cutting soft to medium-hard rocks as an alternative to drilling and blasting in both underground and surface mines. India's commitment to self-reliance in coal has urged the coal companies to adopt mass production and environment-friendly technologies like surface miners in opencast mines. The country's coal production has touched a peak of 893.08 MT in 2022-23, of which production from the open cast is 860.38 MT (96.33%). [3] The application of surface mining for coal production has gained wide acceptance, particularly in mining areas where drilling and blasting are prohibited operationally. [4]

Initially, during the 1970s, surface miners were designed for road cutting, and later on, during the 1990s, the improved drum design and higher machine capacities enabled its application for cutting in-situ rocks like limestone and coal in an eco-friendly and economical manner. In India, surface miners were first introduced on a pilot basis in a limestone mine in 1994 at Gujarat Ambuja Cement Limited due to restrictions on blasting. After that, in 1999, the Wirtgen 2100 SM model was introduced at the Lakhanpur opencast coal mine of Mahanadi Coalfields Limited. [5,6] Since then, many surface miners manufacturers like Wirtgen (SM series), L&T, Puzzolana, Vermeer, Bitelli, Trencor, Huron Manufacturing Co (Easi-miner), Takraf, and Tesmec, etc. have come up with different models and sizes for their application in open cast mines for blast free extraction of material. The applicability of Wirtgen surface miners in different rocks based on unconfined compressive strength (MPa) is shown in Figure 1. [7] Rocks with UCS up to 60 MPa can be cut or extracted economically using surface miners, and rocks with UCS between 60 and 120 MPa can be cut in special applications with reduced performance using surface miners.

Surface miners are crawler-mounted machines, and the most popular type being used in India has a cutting drum positioned below the machine and rotates in an upcutting direction that has its application for extraction of soft to medium hard rock with compressive strengths up to 120 MPa. [8] Globally, surface miners are being used for the extraction of coal, limestone, lignite, salt, phosphate, gypsum, bauxite and iron ore. [9]

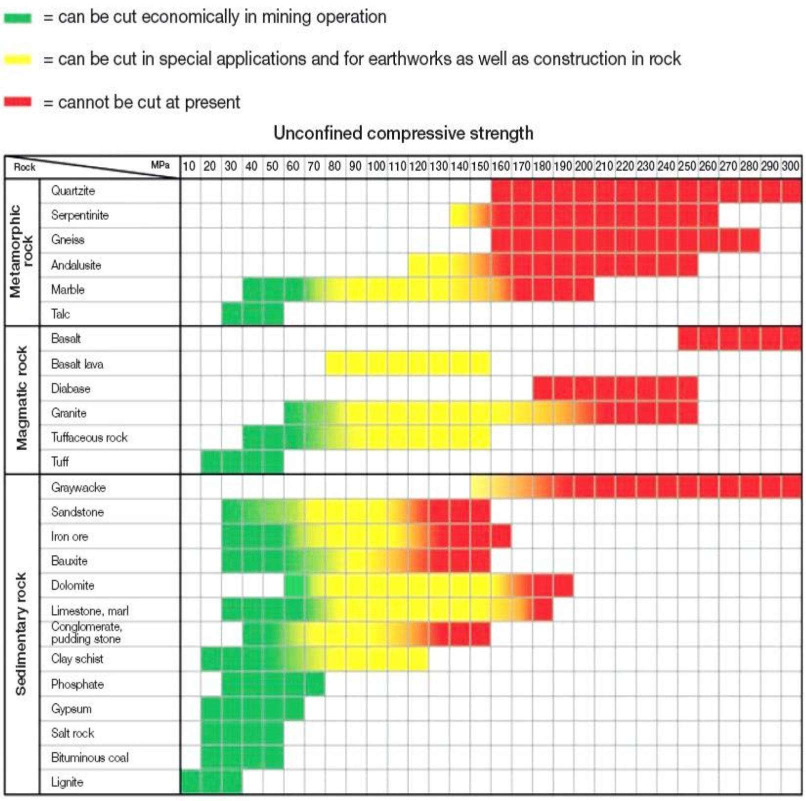


**Fig. 1 Applicability of surface miners in different rocks**

The advantages it offers include working close to habitats, selective mining, simplicity and ease of operation, elimination of drilling and blasting, no primary crushing, uniformly sized material throughput, continuous operation, reduced operating cost, requiring less supervision, maintaining smooth, clean and stable high wall. [10] Generally, conical picks with cemented tungsten carbide inserts are being extensively used in surface miners. The benefits of conical picks over other tools are increased depth of cut, less specific energy consumption, symmetrical wear during cutting, and longer life. [11,12] Cemented tungsten carbide inserts are used because this material has an exceptional combination of strength, modulus of elasticity and hardness. Pick spacing, number of spirals, angular positions between picks, breakout angle, and drum advance speed per revolution influence the pick-cutting interactions. [13] During cutting, the cutting tool hits the coal/rock and the presence of undesirable rock material (i.e., hard rock/bands) in between coal seam results in the sudden high impact of harder rocks on the cutting picks, thereby causing cracking and crushing of WC-Co grains making the cutting pick useless. [14]

The economics of rock cutting using surface miners depends on the achieved rate of production (i.e., productivity) and unit operating cost. The productivity of surface miners is a function of depth of cut, drum width and cutting speed. It was reported that the cutting speed of surface miners while cutting coal in mines of eastern coalfields limited ranged between 12 to 22m/min with an average cutting depth of 0.18m, and the cutting speed was reduced to 12 to 14m/min in portions of hard bands to prevent overloading. [15] The fuel consumption is the major operating cost of the surface miner. [16] Diesel and pick consumption account for around 70% of the total operating cost of surface miners. The actual production and surface miner utilization (hrs) varies significantly in each shift. Within the mines, and utilization of surface miners (hrs) has a positive correlation with production efficiency, i.e., an increase in utilization increases the production. [17] Hence the production, utilization (hrs), diesel and pick consumption are considered as key performance indicators (KPIs) of any surface miner deployment. A very limited study was reported in the literature about estimating the KPIs of surface miners, particularly in coal seams having interlaced dirt bands. Odisha state is blessed with the highest coal resource of 88.104 billion tonnes (BT), accounting for 24.7% of the country's total coal resource, [18] but the coal seams here are characterized by the presence of high ash content and interlaced dirt bands (10cm to 1.5m) which are often termed as rejects. The authors have conducted the study in open cast coal mines of Mahanadi Coalfields Limited (MCL) located in Odisha, where around 75 surface miners of different make and models are in operation; this study takes into account the impact of dirt bands on the cutting performance of surface miner which was not addressed in previous researches. The authors have developed empirical relations for estimating all the KPIs of surface miners considering intact rock, rock mass and machine parameters that are simple and easy to use. Having a knowledge of these KPIs beforehand helps the coal mining companies in selecting the right surface miner taking into account the rock characteristics as well as targeted production.

## 2. Literature Review

The cutting performance of a surface miner depends on numerous factors that can be classified broadly into intact rock parameters, rock mass parameters, machine parameters and operational parameters. Intact rock parameters include moisture content, brittleness index, UCS, density, point load strength index, Young's modulus, toughness index, Brazilian tensile strength, p-wave velocity, cerchar abrasive index, specific energy consumption etc. Rock mass parameters include rock quality designation (RQD), volumetric joint count, stickiness, Schmidt rebound hardness number, Insitu p-wave velocity, presence of joints/discontinuities, dirt bands/intrusions and ash/impurities/silica content, etc. Machine parameters include engine power, cutter power, pick the lacing pattern, break out the angle, pick material, no. of picks, pick orientation, the material of pick, drum width, drum diameter, energy transfer ratio to cutting drum, the weight of the machine, etc. [13]. Operational parameters include windrowing/side-casting/direct loading, wet/dry cutting, available face width, available face length, cutting speed, depth of cut, operator's efficiency, and method of mining (empty travel back method, turn back method and continuous mining method). [19] Prediction of rock cuttability helps in selecting the excavation system. Different researchers used different combinations of parameters for developing empirical equations for determining the KPIs of surface miners which are productivity, pick and diesel consumption. Jones and Kramadibrata (1995) have developed a relation for estimating the production rate of surface miners with respect to UCS based on experimentation data. This equation is applicable in rocks with UCS up to 60 MPa, and there is no consideration of engine power or machine configuration.

$$\text{PR} = 1005 - 559 \,\text{Log}\,(\text{UCS}) \quad (1)$$

Where PR is the production rate ($m^3$/hr), UCS is uniaxial compressive strength.

The manufacturers of surface miners represented the cutting performance solely on the basis of a single rock parameter, i.e., undefined compressive strength, as shown in Figures 2a and 2b. Here, the cutting performance ($m^3$/hr) is based on the volume of material cut with respect to time spent in cutting, i.e., effective cutting hours and does not take into account the time of manoeuvring and servicing. UCS of rock is considered as the most reliable indicator of cuttability and the cutting rate decreases with increasing compressive strength. [20] Figures 2a and 2b [21] show that the cutting performance or instantaneous cutting rate ($m^3$/hr) changes solely with the UCS of rock, which implies that the cutting speed has to be changed proportionally to the cutting depth considering the UCS of rock. The cutting depth and speed are the most influencing operational parameters in determining the productivity of surface miners. [16] Depth of cut is dependent on drum diameter, machine power and type of material. An increase in cutting depth increases the load on the machine, which eventually results in decreasing the cutting speed of the surface miner. [19] per the rock strength/properties because any improper synchronization

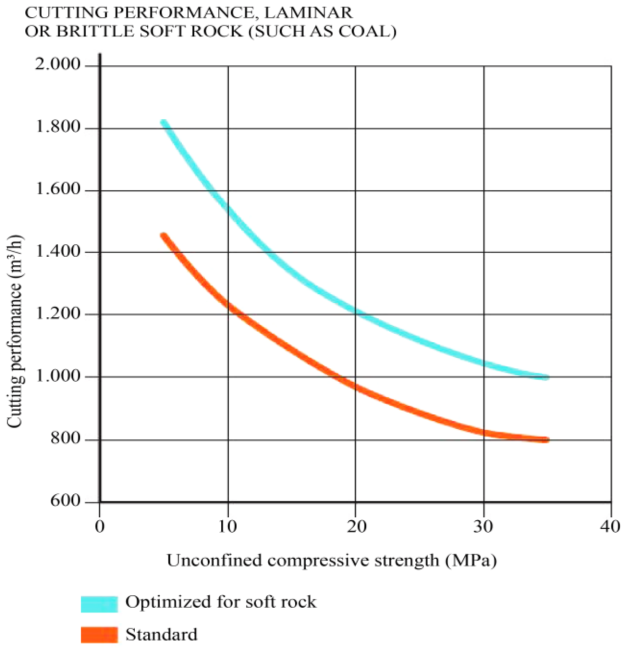


**Fig. 2a Cutting Performance of 2200 SM 3.8**

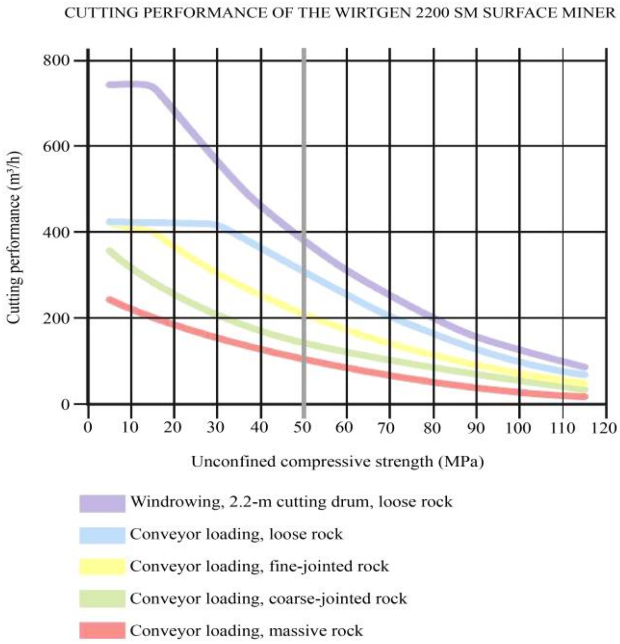


**Fig. 2b Cutting Performance of 2200 SM**

of the same shall lead to premature pick wear. [22] Abrasiveness is one of the important properties of rock/coal that affects the wear of cutting picks and picks maintenance cost, and thus, it influences the production rate. The abrasivity varies from mine to mine and seam to seam due to variations in coal quality. It was reported that the coal quality (silica content) directly impacts the rate of abrasion of cutting picks, and the average life of the pick ranged from 275 hours to 681 hours in mines of SECL. [23] The abrasivity of rock can be determined using the Cerchar abrasivity test which can be used for evaluating the wear of cutting picks of excavation equipment under different geo-mining conditions. Pick wear is a continuous process, and to exactly quantify the same, one has to record the initial weight of picks before the start of cutting and record the final weight of picks after cutting and then correlate the weight loss of all the picks with respect to the quantum of material cut. For doing so, the machine has to be stopped for a significant amount of time, and hence, this is not a practical approach. Picks are replaced only when the tungsten carbide insert is completely worn out and if it is opined that it cannot cut the material any further. No pick replacement on a particular day does not mean there is no pick wear, but it means that none of the picks have reached the condition that warrants pick replacement. So, picks replaced on a daily basis with respect to material cut will have huge variations and so cannot be used for representing the wear rate of picks or pick consumption. It was reported that the correlation coefficient of pick consumption with respect to coal production on a daily basis and monthly basis was found to be 0.6643 and 0.9092. [24] The authors in this paper, therefore, have averaged pick replacements over one month or more so that variations are neglected, and a better representation of pick consumption is obtained.

Based on data from equipment manufacturers and experimental data, Origiliasso C et al. (2014) have developed empirical relations for determining the production rate of a surface miner by considering UCS, abrasivity and engine power as the critical parameters influencing productivity. The production rate takes into account not only the cutting time but also the time spent in ancillary operations such as manoeuvring and servicing.

$$PR = (2 \times Pw - 600) \times e^{-0.024\,(UCS + 10\,(CAI - 0.5))} \quad (2)$$

Where PR is production rate ($m^3$/hr), Pw is engine power (in KW), UCS is uniaxial compressive strength (MPa), and CAI is cerchar abrasivity index (CAI). CAI of 0.5 is considered an easy-to-dig nonabrasive material. [25] Machine power shall have an influence on the production rate. A machine with a higher power and weight can perform better and shall able to cut rocks of higher UCS. However, the main drawback of this equation is that it completely neglects the rock mass characteristics.

For the first time, Dey and Ghose (2008) have developed a cuttability index (CI) that is a composite of point load strength index (Is), volumetric joint count (Jv), rock abrasivity (Aw), direction of cutting with respect to major joint orientation (Js) and machine power (M). This index gives a first-hand idea about "GO-NO GO" on surface miner applicability. [19]

$$CI = Is + Jv + Aw + Js + M \quad (3)$$

CI > 80, surface miners should not be deployed.

$$L^* = \left(1 - \frac{CI}{100}\right) k.Mc \quad (4)$$

Where $L^*$ is cutting performance ($m^3$/hr), Mc is the rated capacity of the machine ($m^3$/hr), CI is the cuttability index, and k varies between 0.5 to 1, leaving a good scope for research. The relationship takes into account intact rock, rock mass, machine and operational parameters. All the above researchers have developed relationships for estimating the productivity of surface miners only.

Very little work was done in predicting all the three KPIs of surface miners thereby leaving a scope for research. The p-wave velocity, also called longitudinal wave or compressional wave, can move through solid rock in the form of compression and expansion in the direction of travel. Measuring in-situ p-wave velocity helps in determining the parameters of rock mass [26]. Insitu p-wave velocity takes into account the presence of joints/discontinuities/fractures and degree of compaction, etc. and thus can be considered as a representative parameter of rock mass. Rocks with higher insitu p-wave velocity are difficult to rip. In-situ p-wave velocity was used for characterizing the rock mass condition at shallow depth and helped in the selection of an excavation system. [27] It was seen that the productivity of a surface miner varies inversely to the in-situ p-wave velocity. Prakash et al. (2015) have performed commendable research and developed a rock cuttability index for surface miners ($RCI_{SM}$) for estimating KPIs of surface miners, mainly productivity, diesel, and pick consumption based on the study undertaken in coal mines and limestone mines together considering intact rock properties defined by Intact Rock Factor (IRF), rock mass properties defined by Rock Mass Factor (RMF) and machine and operational parameters defined by Machine Factor (MF). [28]

$$RCI_{SM} = \frac{1000\ MF}{IRF \times RMF} \quad (5)$$

$$MF = \frac{EP \times CA \times CS}{1000} \quad (6)$$

$$IRF = E \times CAI \times LV_p \quad (7)$$

$$RMF = \frac{IV_p}{RN} \quad (8)$$

Where EP is engine power (kW), CA is the cutting area of the drum ($m^2$). CS is cutting speed (m/min), E is Young's modulus (GPa), CAI is Cerchar Abrasivity Index, $LV_p$ is laboratory p-wave velocity (km/s), $IV_p$ is in-situ p-wave velocity (m/s), and RN is rebound hardness number.

$$CA = LaDW \quad (9)$$

Where DW is drum width, and $L_a$ is the length of the arc in contact with rock (m).

$$L_a = \frac{2\pi R \cos^{-1}[(R-D)/R]}{360} \quad (10)$$

Where R is the drum radius (m), and D is the depth of cut (m).

$$TPH = 181.5\ RCI_{SM}^{0.245} \quad (11)$$

$$DCT = 338\ RCI_{SM}^{-0.19} \quad (12)$$

$$PCT = 2\ RCI_{SM}^{-0.18} \quad (13)$$

Where TPH is production (t/h), DCT is diesel consumption/1000te, and PCT is pick consumption/1000te.

The relationships encompass depth of cut and cutting speed as input parameters, which are dependent on rock strength. Further, the developed relationships include a total of ten (10) different parameters, thereby making the assessment lengthy and complex. In all the previous research, only the engine power (in KW) of the machine was given prominence, with no consideration of the operating weight of the machine. The operating weight of the machine is an important parameter that influences the KPIs of surface miners. As the cutting drum is positioned at the bottom, the machine weight aids in cutting and will help in having better pick penetration [29]. The power-to-weight ratio should be in proportion to ensure proper reaction force to balance the cutting action without any vibrations. This becomes prominent while cutting inseam dirt bands/hard bands, which are interlaced within the coal seam. If the weight of the machine is less then there are chances of machine vibration while cutting dirt bands. The higher the power-to-weight ratio of a machine, the better the fuel efficiency. So, this leaves a scope for research for developing a coal cuttability factor for surface miners that is simple to use for assessment of KPIs of surface miners i.e., normalized production rate, pick and diesel consumption.

## 3. Field Study and Data Collection

The authors have conducted the study in 10 opencast coal mines of Mahanadi Coalfields Limited located in Odisha state. The open cast mines of Mahanadi Coalfields Limited are spread over two Coalfields, i.e., IB coal fields (Jharsuguda and Sundergarh districts) and Talcher Coalfields (Angul district) of Odisha. The geology of the coal deposits in IB fields and Talcher fields varied widely. Around 75 surface miners are in operation at different mines of MCL. The details of the mines are given in Tables 1, 2 and 3. Turn back method is the predominant method of surface miner operation at mines of MCL. Land availability is one of the major problems at open cast mines of MCL, and in such situations, due to a small working face area continuous mining method is adopted. From the field study, it was found that the average depth of cut is maintained in the range of 0.20 to 0.25m. In many cases, the available face length is more than 200m, and the face width is more than 80m. The picks of surface miners are examined by a competent person on the first shift of every day during the maintenance time and the picks which are worn out are replaced with new picks. It takes around 60 to 90 seconds to replace one pick. The surface miner is operated at a reduced speed while cutting the dirt bands. It was observed during the field study that if the speed is not reduced while cutting the dirt bands, then it leads to vibration and overheating of the picks and machine, resulting in reduced pick life and machine breakdown. The configuration of surface miners that have been studied is given in Table 4. [1, 2, 21]

The machine's power ranged from 597KW to 709 KW, and the machine's operating weight ranged from 53.5 te to 76 te. To identify the critical intact rock parameters that influence the cutting performance of surface miners, core samples of NX size of 3m length were collected using the portable core cutting machine at each location from different seams in the above mines. Due care has been taken to collect the representative core samples as practicably as possible such that it includes both coal and inseam dirt bands. The collected samples were packed, and proper nomenclature was assigned, as shown in Figure 3. The collected samples were prepared as per the testing standards required for determining uniaxial compressive strength, Young's modulus, bulk density, laboratory p-wave and s-wave velocity, cerchar abrasivity index, and point load strength index. Insitu p-wave velocity can fairly represent the rock mass conditions. The seismic refraction tomography technique was used for determining the insitu p-wave velocity of coal seams. For performing the study, 24 channel wireless ATOM Geophones, Geometrics were used. Small holes of 1-to-2-inch depth were drilled at either 2m intervals or 3m intervals for placing the geo-phones based on the seam thickness/required depth of investigation. Plaster of Paris was used to ensure healthy contact of geophones with ground movement. 10 kg hammer was used for hitting the ground at offsets of -20, -16, -12, -8, -4, +8, +12, +16 and +20 for geophones placed at 2m and -30, -24, -18, -12, -6, +6, +12, +18, +24, +30 for geophones placed at 3m. A total of 10 readings were taken at each location to improve the signal-to-noise ratio in the data acquired. Care has been taken such that depth of investigation covers the entire seam thickness so that it takes into account the effect of dirt bands/intrusions also. Rebound number, which gives an idea of surface hardness, was also determined for each coal seam using Schimdt's rebound hammer. A total of 49 data sets pertaining to 5 different surface miners models operating in 10 open cast coal mines in different seams that include utilization (Hrs), coal cut ($m^3$), dirt bands cut ($m^3$), diesel consumption (ltrs) and pick consumption (Nos) were generated for deducing KPIs of surface miner i.e., normalized production rate, pick and diesel consumption for cutting 1000$m^3$ of coal and dirt bands as per the Equation 14, 15 and 16 respectively. Utilization (hrs) of surface miner includes the time spent in production activities i.e., cutting and travelling and does not include idle time and maintenance time. Material cut ($m^3$) includes the volume of coal cut ($m^3$) and dirt bands cut ($m^3$) by surface miners. Diesel consumption (ltrs) is the amount of diesel consumed by surface miners in litres during the period of time. Pick consumption (Nos) is the number of picks of a surface miner replaced during a period of time. Production rate (PR) or productivity is defined as the amount of material cut (both coal and dirt bands) in $m^3$ per utilization hour, and normalized production rate (NPR) is defined as the production rate divided by drum width.

$$\mathrm{NPR} = \frac{\mathrm{MC}}{\mathrm{U*DW}} \tag{14}$$

Where NPR is normalized production rate ($m^3$/hr/m), MC is material cut ($m^3$), i.e. the sum of coal cut and dirt bands cut ($m^3$), U is utilization (hr), and DW is drum width (m).

$$\mathrm{PCM} = \frac{\mathrm{PC*1000}}{\mathrm{MC}} \tag{15}$$

Where PCM is pick consumption for cutting 1000$m^3$ of material, PC is pick consumption (Nos), and MC is material cut ($m^3$).

$$\mathrm{DCM} = \frac{\mathrm{DC*1000}}{\mathrm{MC}} \tag{16}$$

Where DCM is diesel consumption for cutting 1000$m^3$ of material, DC is diesel consumption (ltr), and MC is material cut ($m^3$). 44 data sets were used for developing the model, while 5 data sets were kept aside such that they covered different surface miner models and rock characteristics for validation of the model. The descriptive statistics of 44 observations of intact rock parameters (sl. No 1 to 7), rock mass parameters of different seams (sl. No 8 to 10), machine parameters (sl. no. 11) and KPIs of 5 models of surface miners (sl. no. 17 to 19) are shown in Table 5.

**Fig. 3 Collected core samples**

**Fig. 4 Set up for assessment of Insitu p-wave velocity**

**Table 1. Salient features of mines at talcher coalfields**

| Sl. No | Description | Ananta | Balram | Lingaraj | Bhubaneswari |
|---|---|---|---|---|---|
| 1 | Mineable Reserve (in MT) | 366.67 | 192.64 | 321.50 | 374.12 |
| 2 | Stripping Ratio ($m^3$/te) | 2.21 | 2.21 | 0.69 | 0.67 |
| 3 | Working Coal Seams During Study Period | IV, V B, VI T | II E, III E, IV | II, III, V, VI A | II, III |
| 4 | Gradient of Coal seams | 5 to $11^0$ | 1 in 10 | $14^0$ | 1 in 12 to 15 |
| 5 | Average Thickness (m) | 6.15, 4.21,4 | 6.97, 3.88, 3.19 | 39.28, 12.5,10.22, 8.5 | 30, - |
| 6 | Mine Capacity (in MT) | 15 | 8 | 16 | 20 |
| 7 | Life of Mine | 26 | 25 | 21 | 25 |

**Table 2. Salient features of mines at IB valley coalfields**

| Sl. No | Description | Lajkura | Samaleswari | Belpahar | Lakhanpur |
|---|---|---|---|---|---|
| 1 | Mineable Reserve (in MT) | 69.4 | 112.26 | 63.33 | 358.58 |
| 2 | Stripping Ratio (m3/te) | 3.4 | 3.4 | 2.19 | 2.34 |
| 3 | Working Coal Seams During Study Period | Lajkura | Lajkura | Rampur | Lajkura |
| 4 | Gradient of Coal seams | 1 in 16 | 1 in 18 | 1 in 10 to 14 | 50 |
| 5 | Thickness (m) | 6.57 to 12.54 | 6.4 to 13.16 | 0.2 to 8.74 | 20.88 to 33.53 |
| 6 | Mine Capacity (in MT) | 2.5 | 12 | 8 | 15 |
| 7 | Life of Mine | 29 | 10 | 10 | 25 |

**Table 3. Salient features of mines at basundhara coalfields**

| Sl. No | Description | Garjanbahal | Kulda |
|---|---|---|---|
| 1 | Mineable Reserve (in MT) | 229.25 | 323.05 |
| 2 | Stripping Ratio (m3/te) | 0.98 | 0.96 |
| 3 | Working Coal Seams During Study Period | Lajkura, Rampur | Lajkura, Rampur |
| 4 | Gradient of Coal seams | 1 in 11 to 19 | 1 in 10 to 11 |
| 5 | Thickness (m) | - | 2.98 to 31.89, 2.3 to 17.83 |
| 6 | Mine Capacity (in MT) | 10 | 15 |
| 7 | Life of Mine | 28 | 21 |

**Table 4. Specifications of different surface miner models**

| Sl. No | Make | Model | Drum Width (m) | Drum Radius (m) | Power (KW) | Max Cutting Depth (m) | Cutting picks (Nos) | Operating Weight (Kg) | Max Operating Speed (m/min) | Engine power to Weight ratio (KW/Te) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | L&T | KSM-303 | 3 | 0.575 | 597 | 0.3 | 106 | 53500 | 30 | 11.15 |
| 2 | L&T | KSM-403 | 4 | 0.575 | 709 | 0.3 | 136 | 57500 | 25 | 12.32 |
| 3 | Puzzolana | PMM-2205 | 4 | 0.6 | 671 | 0.3 | 111 | 76000 | 85 | 8.82 |
| 4 | Wirtgen | 2200 SM 3.8 | 3.8 | 0.65 | 709 | 0.35 | 100 | 53800 | 85 | 13.17 |
| 5 | Wirtgen | 220 SMi 3.8 | 3.8 | 0.65 | 709 | 0.35 | - | 58050 | 85 | 12.20 |

**Table 5. Descriptive statistics of input and output variables**

| Sl. No | Parameter | Min | Max | Range | Mean | Standard Deviation | Median |
|---|---|---|---|---|---|---|---|
| 1 | UCS (MPa) | 13.61 | 29.31 | 15.70 | 21.56 | 3.18 | 22.32 |
| 2 | Young's Modulus (GPa) | 1.15 | 4.04 | 2.89 | 2.08 | 0.72 | 2.04 |
| 3 | Laboratory P-wave velocity (m/s) | 1362 | 2170 | 808 | 1649.30 | 202.44 | 1633.50 |
| 4 | Laboratory S-wave velocity (m/s) | 813 | 1272 | 459 | 875.61 | 68.11 | 865.50 |
| 5 | Point Load Strength Index (MPa) | 0.50 | 1.37 | 0.87 | 0.73 | 0.22 | 0.69 |
| 6 | Bulk Density (g/cc) | 1.19 | 2.05 | 0.86 | 1.56 | 0.24 | 1.56 |
| 7 | Cerchar Abrasivity Index | 0.11 | 0.22 | 0.11 | 0.16 | 0.03 | 0.15 |
| 8 | Insitu p-wave velocity (m/s) | 640 | 1570 | 930 | 1040.57 | 244.89 | 1010 |
| 9 | Insitu s-wave velocity (m/s) | 560 | 771 | 211 | 675 | 64.76 | 683.5 |
| 10 | Rebound Number (RN) | 19 | 50 | 31 | 40.25 | 6.41 | 40 |
| 11 | Power to weight ratio (Kw/te) | 8.82 | 13.16 | 4.34 | 11.10 | 1.61 | 11.14 |
| 12 | Utilization (Hrs) | 156 | 458 | 302 | 317.02 | 70.39 | 325 |
| 13 | Coal cut ($m^3$) | 38166 | 191700 | 153534 | 106800.1 | 38685.38 | 104257.5 |
| 14 | Dirt bands cut ($m^3$) | 0 | 95142 | 95142 | 10765.09 | 19664.36 | 5520.5 |
| 15 | Pick consumption (Nos) | 68 | 400 | 332 | 201.2727 | 70.4 | 199.5 |
| 16 | Diesel consumption (ltr) | 11589 | 48623 | 37034 | 31660.86 | 8161.53 | 32639.5 |
| 17 | PCM | 0.80 | 5.47 | 4.67 | 1.91 | 0.92 | 1.76 |
| 18 | DCM | 159.48 | 556.92 | 397.45 | 299.64 | 107.44 | 260.70 |
| 19 | Normalized Production Rate (NPR) | 45.56 | 158.92 | 113.37 | 99.06 | 30 | 93.09 |

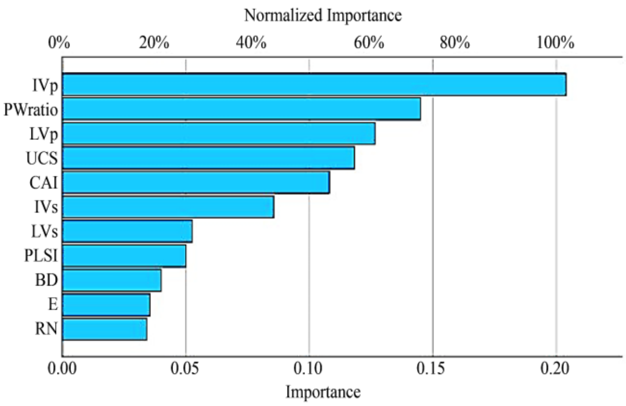


**Fig. 5 Normalized importance of critical parameters influencing surface miner performance**

## 4. Results and Discussions

### *4.1. Development of Coal Cuttability Factor for Surface Miner*

To identify the critical parameters and relative importance of different parameters on all three key performance indicators of surface miners, an Artificial Neural Network (ANN) analysis was performed with eleven (11) input parameters and three (3) output parameters. It was found that Insitu p-wave velocity, the power-to-weight ratio of the surface miner, laboratory p-wave velocity, UCS, and CAI have normalized importance of more than 50%, as shown in Figure 5. So, these parameters are considered for the development of a coal cuttability factor for surface miners ($CCF_{SM}$). It was found that a combination of UCS, laboratory and insitu p-wave velocity, and the power-to-weight ratio of the machine is well correlated with normalized production rate, pick and diesel consumption of surface miner for cutting 1000$m^3$ of material as shown in Figure 6.

$$CCF_{SM} = \frac{(\text{UCS x LVp})}{(\text{IVp x}\frac{\text{EP}}{\text{OW}})} \quad (17)$$

Where UCS is uniaxial compressive strength (in Mpa), $LV_p$ is laboratory p-wave velocity (in m/s), $IV_p$ is insitu p-wave velocity (in m/s), EP is engine power (in KW), and OW is operating weight of the machine (in te). The coal cuttability factor thus developed is a composite of intact rock parameters, rock mass parameters and machine parameters. The coal cuttability factor was closely associated with normalized production rate ($m^3$/hr/m), diesel consumption (litres/1000$m^3$) and pick consumption (Nos/1000$m^3$) with an index of determination ($R^2$) of 0.736, 0.768 and 0.713, respectively in the exponential form as shown below in Figure 7, 8 and 9 respectively. Different make/model has different drum width and drum radius and thus has different production capacities. So, to eliminate/nullify the impact of drum width on the production of surface miners, production was normalized with respect to drum width.

Normalized Production Rate (NPR) is defined as the volume of material cut in one hour per unit width of drum and is expressed in $m^3$/hr/m. It was found that combining the cerchar abrasivity index (CAI) with the coal cuttability factor further improved the index of determination ($R^2$) for estimating pick consumption for 1000$m^3$ of material cut to 0.816. The relations for estimating Normalized Production Rate (NPR), Diesel Consumption (DCM), and Pick Consumption (PCM) for cutting 1000$m^3$ of coal and dirt bands are as follows:

$$NPR = 252.77\, e^{-0.301*CCF_{SM}} \quad (18)$$

$$DCM = 105.52\, e^{0.3014*CCF_{SM}} \quad (19)$$

$$PCM = 0.6895\, e^{1.7368*CAI*CCF_{SM}} \quad (20)$$

From equations 18, 19 and 20, one can easily predict the achievable production rate and also diesel and pick consumption for 1000$m^3$ of material cut by a surface miner with ease, which are considered as main economic parameters in the deployment of the surface miner.

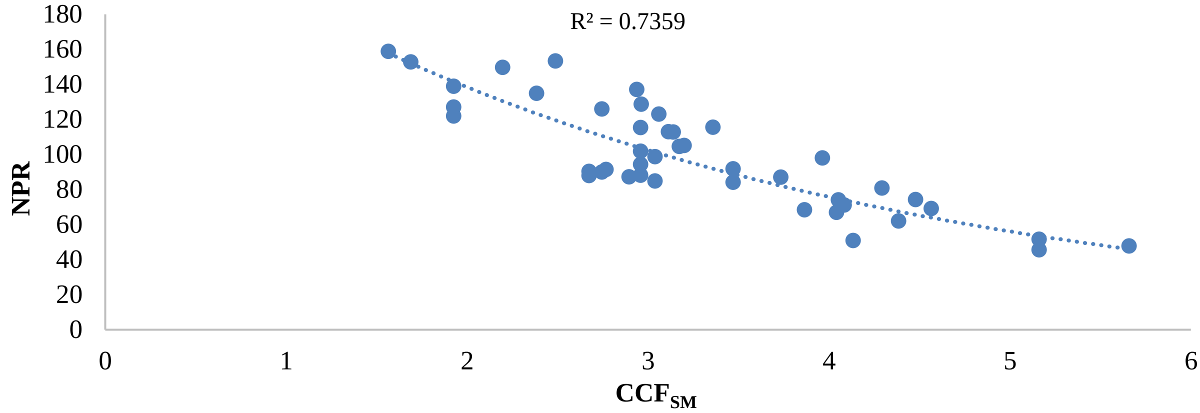


**Fig. 6 Relation between NPR and $CCF_{SM}$**

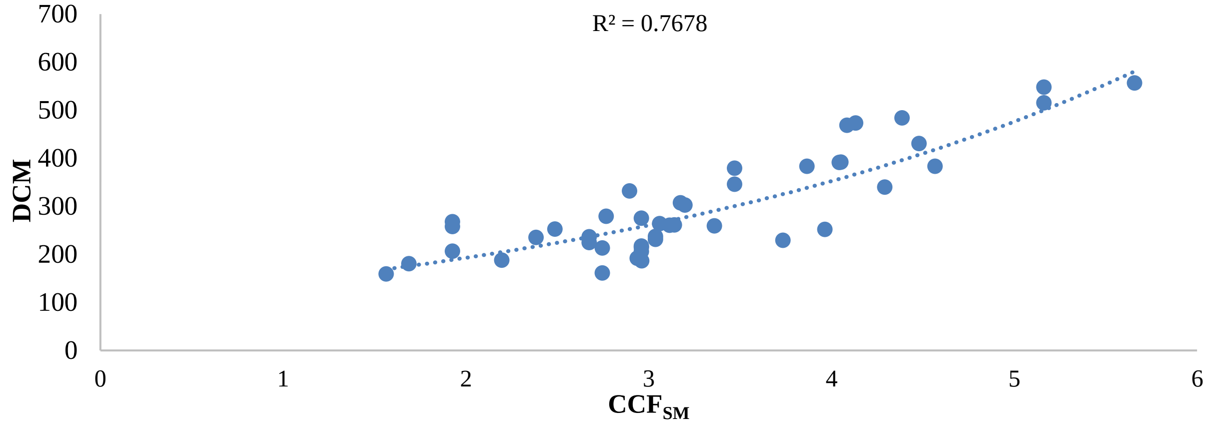


**Fig. 7 Relation between DCM and $CCF_{SM}$**

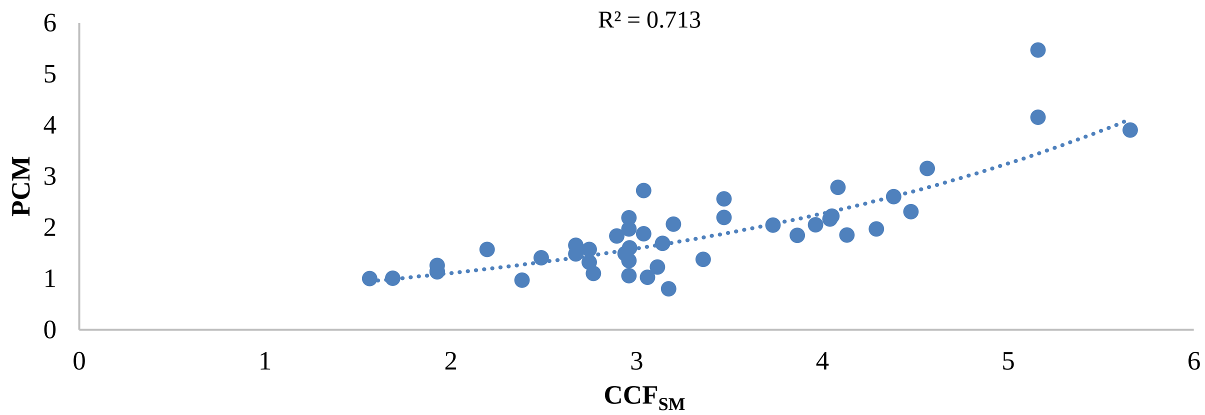


**Fig. 8 Relation between PCM and $CCF_{SM}$**

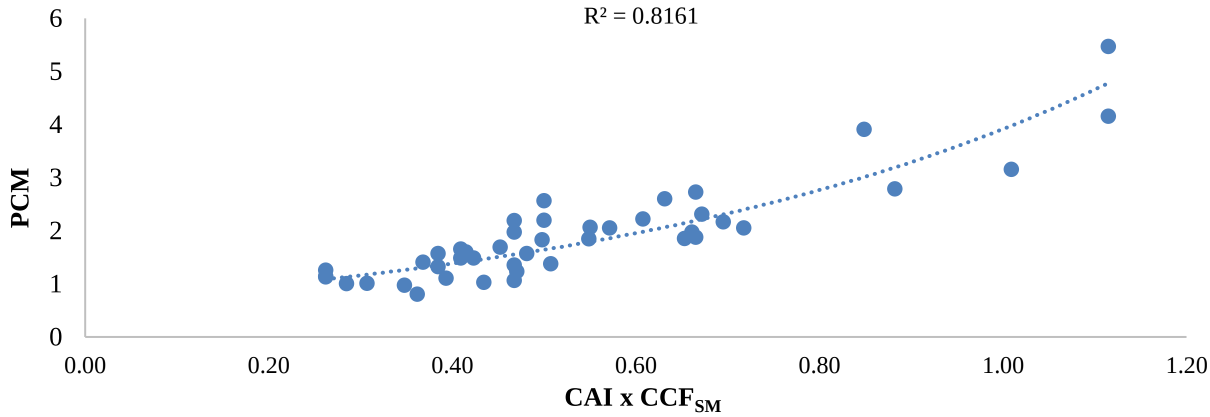


**Fig. 9 Relation between PCM and CAI x $CCF_{SM}$**

**Table 6. Data for validation**

| Name of OCP | SM Model | Avg. UCS (Mpa) | P-wave velocity (m/s) | Avg. CAI | Insitu p-wave velocity (m/s) | Power to Weight Ratio (KW/Te) |
|---|---|---|---|---|---|---|
| Bhubaneswari | 2200 SM 3.8 | 22.12 | 1464 | 0.231 | 1074 | 13.16 |
| Kulda | 220 SMi 3.8 | 20.78 | 2032 | 0.146 | 1453 | 12.20 |
| Garjanbahal | KSM 303 | 24.33 | 1819 | 0.158 | 1215 | 11.14 |
| Lingaraj | PMM 2205 | 19.58 | 1419 | 0.172 | 780 | 8.82 |
| Lingaraj | KSM 403 | 23.65 | 1651 | 0.144 | 1010 | 12.31 |

**Table 7. Validation of pick consumption per 1000m$^3$**

| SM Model | $CCF_{SM}$ | Actual PCM | Predicted PCM | % error |
|---|---|---|---|---|
| 2200 SM 3.8 | 2.292 | 1.782 | 1.73 | 2.92 |
| 220 SMi 3.8 | 2.382 | 1.169 | 1.262 | -7.95 |
| KSM 303 | 3.270 | 1.520 | 1.692 | -11.32 |
| PMM 2205 | 4.041 | 1.932 | 2.306 | -19.36 |
| KSM 403 | 3.139 | 1.347 | 1.512 | -12.29 |

**Table 8. Validation of diesel consumption per 1000m$^3$**

| SM Model | $CCF_{SM}$ | Actual DCM | Predicted DCM | % error |
|---|---|---|---|---|
| 2200 SM 3.8 | 2.292 | 191.997 | 210.521 | -9.65 |
| 220 SMi 3.8 | 2.382 | 209.002 | 216.359 | -3.52 |
| KSM 303 | 3.270 | 292.605 | 282.7 | 3.39 |
| PMM 2205 | 4.041 | 338.053 | 356.712 | -5.52 |
| KSM 403 | 3.139 | 272.640 | 271.786 | 0.31 |

**Table 9. Validation of normalized production rate**

| SM Model | $CCF_{SM}$ | Actual NPR | Predicted NPR | % error |
|---|---|---|---|---|
| 2200 SM 3.8 | 2.292 | 148.714 | 126.813 | 14.73 |
| 220 SMi 3.8 | 2.382 | 145.287 | 123.396 | 15.07 |
| KSM 303 | 3.270 | 99.153 | 94.472 | 4.72 |
| PMM 2205 | 4.041 | 84.339 | 74.894 | 11.20 |
| KSM 403 | 3.139 | 106.405 | 98.261 | 7.65 |

## 5. Model Validation

5 data sets were taken out from the generated data such that they cover different surface miner models and rock characteristics for the purpose of validation of the model. The data used for validating the empirical equations 18, 19 and 20 was given in Table 6, and the results of validation of pick consumption, diesel consumption and normalized production rate were given in Tables 7, 8 and 9, respectively. The % error of predicted pick consumption from actual pick consumption varied between 2.92% to -19.36%. The % error of predicted diesel consumption from actual diesel consumption varied between 3.39% to -9.65%. The % error of the normalized production rate from the actual production rate varied between 4.72% to 15.07%. As a whole, the % error in all the KPIs of surface miners, i.e., normalized production rate, pick and diesel consumption with respect to coal cuttability factor, is within 20%.

Hence, the results seem to be in close agreement with the actual measurement in the field, considering mining activity is dynamic in nature. It has many elements that cannot be factored in, like pick replacement criteria changes from mine to mine, operator's efficiency, rainfall, etc. Thus, the developed $CCF_{SM}$, together with CAI, can be used for predicting the KPIs of surface miners with greater precision.

The model can further be finetuned with more data and more machine models for its application under different geotechnical conditions.

## 6. Conclusion

Around 75 surface miners of different make and models are in operation at different mines of MCL. The coal seams in these mines are characterized by the presence of intermittent dirt bands of shale or sandstone, which affects the cutting performance of surface miners. The operation of 5 different models of surface miners in 10 opencast mines of MCL were studied. For having a clear picture of coal seams and dirt bands cores of NX size of 3m length were collected using portable core cutting machines. The samples are prepared as per standards for the determination of seven (7) intact rock properties in the rock mechanics laboratory. 24-channel geo-phones are used for determining the in situ p-wave velocity of coal seams for the entire thickness so that the influence of intermittent dirt bands is also fairly considered Critical parameters that nfluence the performance indicators of surface miners were identified using ANN analysis. A new coal cuttability factor for surface miners ($CCF_{SM}$) was developed that is a composite of uniaxial compressive strength (MPa), laboratory p-wave velocity (m/s), insitu p-wave velocity (m/s) and power-to-weight ratio (Kw/te) of the machine. Thus, the factor includes intact rock, rock mass and machine parameters. The key performance indicators of surface miners, i.e., normalized production rate, pick and diesel consumption for cutting 1000m$^3$ of material, showed a strong relationship with $CCF_{SM}$.

It was found that combining the cerchar abrasivity index (CAI) with $CCF_{SM}$ further improved the relation for predicting pick consumption. Empirical relationships for predicting all the key performance indicators of surface miners were developed. The index of determination ($R^2$) for estimating normalized production rate (m$^3$/hr/m), pick consumption and diesel consumption for cutting 1000m$^3$ of coal and dirt bands was found to be 0.73, 0.82 and 0.77, respectively. The models have been validated, and the results were found to be in close agreement with the actual field data. The models help the mining companies in selecting the surface miner that fulfils the targeted production at a lower operating cost.

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