Influence of Rockmass Properties on Excavation Performance of Mining Shovel

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Abstract

The demand of sustainable practices in mining industry is progressively increasing. The key factors mostly focused for sustainability include environment, safety, economy, and community. However, effective, and efficient working of mine machinery is the core part of sustainable mining practices. Surface extraction of mineral requires a lot of mine machineries due to a rising demand from end-user. Thus, effective, and efficient performance of these costly machines is one of the major challenges and hence, their performance evaluation is necessary. Shovel-Truck system is a widely used material excavation and transportation system in open-pit mines. Efficiency of the shovel has a critical role in increasing production. A huge capital and operating cost are spent over the shovel units. Therefore, proper utilization of these equipment is important to make the project economically viable. Excavation performance of shovel depends largely upon the rockmass properties. This research is conducted in an open-pit lignite mine at Thar Coalfield, Sindh, Pakistan. Shovel performance was monitored in the field to acquire data during excavation process. The truck loading time (LT) of shovel was considered as critical operational parameter in this study which was obtained from the time-study analysis of shovel operation. Various rockmass properties at different working-levels were assessed and correlated with the corresponding loading time. These rockmass properties are attributed as the performance indicators for the shovel operation in this study. This research is useful for mine-production engineers in making production forecasts, shovel-deployment decisions and also help regulators to utilize the data for optimum tariff for upcoming mining projects at Thar.

Keywords: *Truck Loading Time; Shovel-Truck System; Excavation Performance, Sustainable Mining Practice; Open-pit Coal Mining*

1. Introduction

Open pit mining is the most common surface exploitation technique. An Open Pit Mine consists of a series of benches (horizontal layers of material) from which the material is to be extracted. Open-pit mining is suitable for the mineral/coal/ore deposits located near to the surface. The decision lies mainly over the Stripping Ratio, whether to practice surface mining or underground mining method [1]. Rise in the demand of mineral commodities has led the surface mines towards heavy mechanized systems for overburden removal and mineral extraction. These equipment include draglines, shovel-truck systems, and bucket wheel excavators (BWEs). These equipment are quite costly in terms of capital, operation and maintenance. Therefore the proper utilization of these equipment is considered core element of sustainable mining practices [2, 3].

Shovel-Truck system is a common material excavation and haulage system in open-pit coal mines. The production capacity of any open-pit mine is directly influenced by the efficiency of the shovel. Therefore, the shovel performance plays a critical part in mine life and mine economics. The capabilities of mining shovels have gradually improved over the past years [4]. Due to these developments in machinery and technology, the use of hydraulic shovels has gained popularity, particularly in soft sedimentary rocks. Excavation in soil is comparatively easier owing to loose

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consolidation; hence there is lesser difficulty in digging and quick filling of the bucket. In tropical regions, the surface rocks produce thick weathering profiles. Thick weathering profiles may give rise to the irregularity of parent rock [5]. An appropriate assessment of characteristics associated with these irregularities should be carried out for planning a sustainable and cost-effective mining system. For instance, the combinations of sandstone, siltstone, and claystone possess huge dissimilarities in their engineering properties; they can also be encountered inside the same rock mass inter-layered with each other. Layers having high strength can be found to be inter-bedded between the layers having lower strength, which may support or hinder during excavation. Furthermore, sedimentary rockmasses possess discontinuities at a range of scales. Thickness, orientation of bedding and spacing of joints are also the components which may complicate rock mass characteristics [6].

Water content may also affect weak rocks and create a big challenge by altering properties of a few minerals. Water is absorbed very well by a few of the secondary minerals and in this way the original rock strength is decreased. Water content of rock increases due to heavy rainfall particularly for those rocks which are highly to completely weathered because of the free interaction between grains. It has been observed that even a small a rise of 1% in moisture content of any rock, has a considerable impact on its strength and deformability [7]. Therefore, it is essential to be familiar with the physical and mechanical characteristics of rocks, as well as the behaviour of geomaterials. The selection of an excavating equipment and subsequent performance of the machine are impacted more competently by geological and geo-mechanical factors [8]. The selection of excavating equipment must be based on optimum productivity to avoid the production delays and losses. It becomes compulsory to distinguish the properties of different rocks present in an open-pit mines, and to match the digging capabilities of excavating equipment with these properties of excavated material to optimize the loading performance. This study is focused on the effect of rockmass properties on the excavation performance of mining shovel.

2. Previous Studies

The excavation cost can be reduced by a satisfactory assessment of geotechnical characteristics of rock masses. A number of preliminary empirical excavability classifications have been developed to decide excavability by considering material and mass properties of rocks [9, 10]. Random statistical methods were applied in the past to show excavator productivity using different variables. Multiple regression models were developed to show excavator productivity by utilizing the bucket fill factor, depth of digging and swing angle as independent variables. An artificial neural network was also applied in the past for calculating excavator productivity. In previous research, the grain size is effective on degree of filling. It was found that the swell factor has a positive effect on grain size [11].

In many cases, the performance of the excavating machine is not optimized since the connections between the properties of the material being loaded and machine performance parameters have not been carefully investigated. Shovel productivity can be influenced by truck-shovel matching, operator’s skills and practices and operating conditions; rock breakage and material ease of excavation [12]. However, truck productivity depends on capacity of shovel, operator’s skills, material characteristics (swell factor, density) bucket fill factor, truck size, engine power, drive system, fleet management efficiency and haul roads conditions. The capacity of the truck should not exceed 6 to 8 times shovel bucket capacity and shovel should have appropriate height and reach [13]. Table 1 shows different rock parameters affecting on shovel performance considered by different researchers.

Table 1. Summary of rock parameters considered by researchers

Author and Year	UCS	JC	SHV	SWV	TS	W	PLS	GC	D	GSI	RQD	CAI	MC	SDI	ML	SF
Kujundžic et al. (2021)								✓							✓	
Metin and Hakki (2019)									✓							
Dotto M. S. et al. (2018)								✓							✓	✓
Avchar et al. (2017)	✓	✓	✓	✓	✓		✓		✓		✓	✓	✓	✓		
Liang et al. (2015)	✓	✓	✓		✓		✓		✓							
Yazdani and Yakchali (2013)	✓				✓						✓					
Tosun and Konak (2012)								✓								
Demirel (2011)										✓						
Tumac et al. (2007)	✓		✓													
Sari et al. (2007)								✓								
Singh et al. (2007)								✓								
Segarra et al. (2007)							✓		✓							
Osanloo and Hekmat (2005)								✓								
Clark et al. (2004)								✓								
Onederra et al. (2004)								✓								
Hadjigeorgio and Poulin (1998)					✓	✓										
Karpuz (1994)	✓	✓	✓	✓		✓										
Scoble and Muftuoglu (1984)	✓	✓				✓										

UCS = Uniaxial Compressive Strength	W = Weathering	RQD= Rock Quality Designation
JC = Joint Characteristics	PLS = Point Load Strength	CAI = Cerchar Abrasivity Index
SHV = Schmidt Hardness Value	GC = Granulometric Composition	MC = Moisture Content
SWV = Seismic Wave Velocity	D = Density	SDI = Slake Durability Index
TS = Tensile Strength	GSI = Geological Strength Index	ML = Material Looseness
SF = Swell Factor		

3. Materials and Methods

The rock testing was conducted at the Rock Mechanics Laboratory, Department of Mining Engineering, Mehran UET, Jamshoro. Five rockmass properties including uniaxial compressive strength, tensile strength, cohesion, internal angle of friction and wet bulk density were determined using ISRM standard methods for rock characterization [14]. The site investigations were carried out at an open-pit Lignite mine, Block-II, Thar Coalfield, Pakistan. Short-term performance measurements of hydraulic type mining Shovels have been carried out at various working levels (benches). Digging operation of the Shovels were carefully recorded using high-definition camera on the site. Truck Loading times were then extracted from the actual performance recordings of the shovels on the site. The bucket capacity of hydraulic shovels was 7 m^3.

The description of the parameters considered in this study is given below:

i) **Truck Loading Time:** the total time a Shovel or excavator takes to fill one truck bed with the required estimated number of buckets. Sometimes the number of buckets may exceed the estimated number of buckets due to the poor fragmentation of the rocks and the efficiency of the operator.

ii) **Uniaxial Compressive Strength:** the maximum load bearing capacity of a rock specimen under uniaxial compression.

iii) **Tensile Strength:** the peak diametral tension at which the disc specimen fails under uniaxial compression.

iv) **Cohesion:** the internal force between the rock particles which holds the particles intact. It is measured as 'force per unit area' like stress or strength, hence it is also known as cohesive strength. It is basically a parameter related with the shear strength of the rocks/soils signified from Mohr-Coulomb's failure criterion.

v) **Internal Angle of Friction:** It is a shear strength parameter from Mohr-Coulomb's failure criterion, to describe the frictional-shear resistance within rock and soil particles together with the normal effective stress.

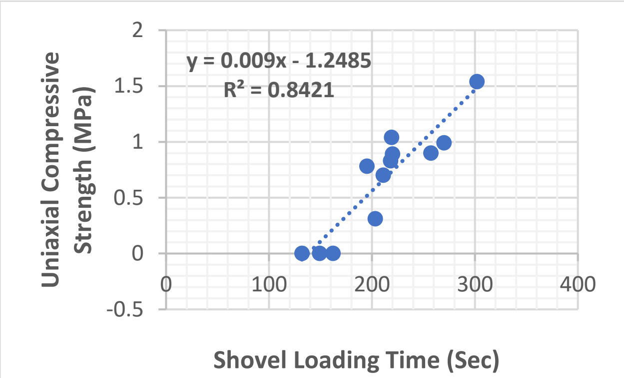
vi) **Wet Bulk Density:** It is the total weight of rock or soil particles (including the inter-granular air or water space) per unit volume.

4. Results, Statistical Analysis and Discussion

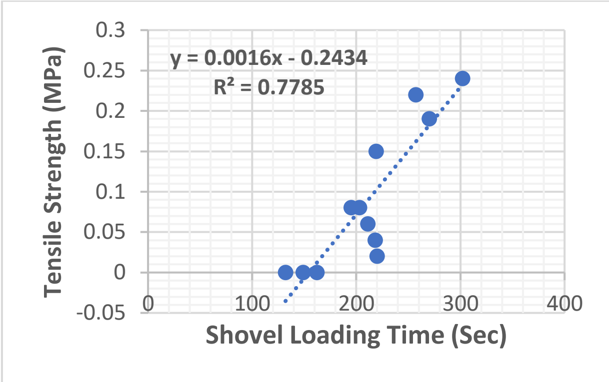
Table 2 presents the Truck loading times at different levels and the corresponding rockmass properties. The rockmass properties are correlated with the loading time of the Trucks, as presented in Fig 1 (a – e).

Table 2. Properties of different rock units and corresponding loading times

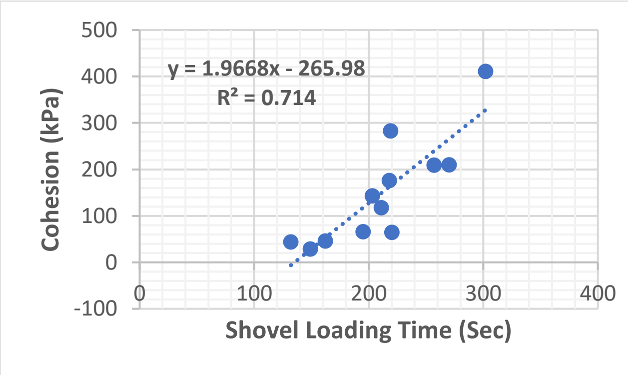
S. No.	Rock Type	Formation	AMSL	SHOVEL PARAMETERS			ROCK PROPERTIES				
				Shovel ID	Shovel Bucket Capacity	Truck Loading Time	Avg. UCS	Avg. Tensile Strength	Avg. Cohesion	Avg. Friction Angle	Avg. Density
			(m)		(m^3)	(sec)	(MPa)	(MPa)	(kPa)	(deg.)	(t/m^3)
1.	Dune Sand	Recent	32	1009	7	132	0	0	44	33	2.04
2.	Dune Sand	Recent	24	1011	7	162	0	0	46	31	2.05
3.	Dune Sand	Recent	18	1015	7	149	0	0	29	32	2.04
4.	Sandstone	Recent	12	1009	7	195	0.78	0.08	66	37	2.03
5.	Sandstone	Recent	6	1005	7	218	0.83	0.04	176	26	2.06
6.	Sandstone	Recent	6	1018	7	257	0.9	0.22	209	43	2.1
7.	Siltstone	Sub-Recent	-6	1006	7	220	0.89	0.02	65	27	2.05
8.	Siltstone	Sub-Recent	-12	1003	7	203	0.31	0.08	143	30	2.04
9.	Siltstone	Sub-Recent	-18	1007	7	270	0.99	0.19	210	24	2.18
10.	Siltstone	Sub-Recent	-18	1013	7	211	0.7	0.06	118	18	2.17
11.	Claystone	Sub-Recent	-36	1014	7	302	1.54	0.24	411	47	2.23
12.	Claystone	Sub-Recent	-48	1012	7	219	1.04	0.15	283	24	2.17



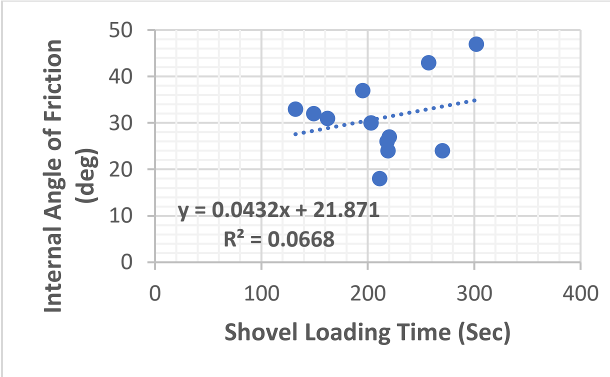
(a)



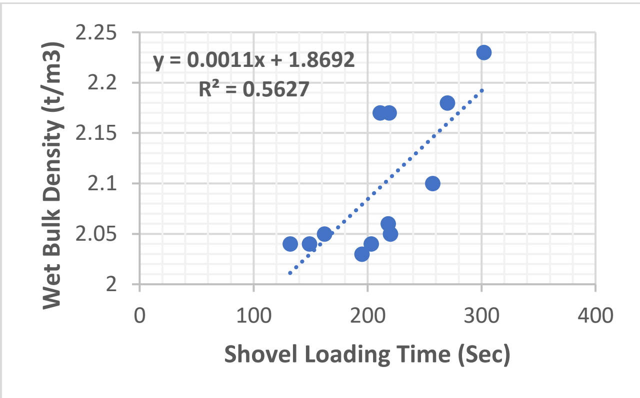
(b)



(c)



(d)



(e)

Fig 1. (a – e) Correlations between Truck Loading Time and Rock Properties

The statistical analysis presented above shows strong correlation between loading time of the Truck (LT) and Uniaxial Compressive Strength, Tensile strength, and Cohesion of the rocks. A moderate correlation was found between the loading time and wet bulk density of the rocks. However, no correlation was observed between the internal friction angle of rock and Truck loading time.

Summary of the statistical analysis is presented in Table 3.

Table 3. Summary of the Statistical Analysis

Parameters Correlated	Equation	R^2
Shovel Loading Time (LT) and Uniaxial Compressive Strength (UCS) of Rocks	**UCS = 0.009(LT) - 1.2485**	**0.8421**
Shovel Loading Time (LT) and Tensile Strength (TS) of Rocks	**TS = 0.0016(LT) - 0.2434**	**0.7785**
Shovel Loading Time (LT) and Cohesion (C) of Rocks	**C = 1.9668(LT) - 265.98**	**0.714**
Shovel Loading Time (LT) and Internal Friction Angle (Phi) of Rocks	**Phi = 0.0432(LT) + 21.871**	**0.0668**
Shovel Loading Time (LT) and Wet Bulk Density (ρ) of Rocks	**ρ = 0.0011(LT) + 1.8692**	**0.5627**

5. Conclusions

This research work presents a novel approach to develop the diggability index for the Thar coalfield Pakistan. The outcomes of this study provide comprehensive solutions to the production scheduling problems and optimization of production operations at Thar. The major decision for mine production engineers in open-pit mines is related to the Shovel deployment. In order to meet the short-term production target, accurate number of Shovels must be deployed at each working level. This deployment decision is based upon the production target and shovel performance. The excavation performance of shovel depends largely upon properties of the rockmass which is being excavated. This study focused on the effect of rockmass properties on the excavation performance of Shovel. The Truck loading time was considered as the key indicator of the shovel performance. Four major lithological units were considered to develop a correlation between the loading time of Truck and corresponding rock properties. It was found that the uniaxial compressive strength is the most significant rock property which affects the excavation performance of mining shovel. It was also observed that the internal friction angle of rocks has no effect on the loading time.

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References

[1] W. A. Hustrulid, M. Kuchta, and R. K. Martin, *Open pit mine planning and design, two volume set & CD-ROM pack*. CRC Press, 2013.

[2] E. Bakhtavar, K. Shahriar, and K. Oraee, "Transition from open-pit to underground as a new optimization challenge in mining engineering," *Journal of Mining Science,* vol. 45, no. 5, p. 485, 2009.

[3] R. Mena, E. Zio, F. Kristjanpoller, and A. Arata, "Availability-based simulation and optimization modeling framework for open-pit mine truck allocation under dynamic constraints," *International Journal of mining science and Technology,* vol. 23, no. 1, pp. 113-119, 2013.

[4] M. Liang, E. T. Mohamad, I. Komoo, and C.-K. Ma, "An excavatability classification system for surface excavation in sedimentary rocks," *Bulletin of Engineering Geology and the Environment,* vol. 76, no. 1, pp. 241-251, 2017.

[5] C. Karpuz, "A classification system for excavation of surface coal measures," *Mining Science and Technology,* vol. 11, no. 2, pp. 157-163, 1990.

[6] J. Hadjigeorgiou and R. Poulin, "Assessment of ease of excavation of surface mines," *Journal of terramechanics,* vol. 35, no. 3, pp. 137-153, 1998.

[7] A. Hawkins and B. McConnell, "Sensitivity of sandstone strength and deformability to changes in moisture content," *Quarterly Journal of Engineering Geology and Hydrogeology,* vol. 25, no. 2, pp. 115-130, 1992.

[8] A. Avchar, B. Choudhary, G. Budi, and U. G. Sawaiker, "Applicability of size-strength rippability classification system for laterite excavation in iron ore mines of Goa," *ASME Journal-ASME IIETA Publication Series Modelling, Measurement and Control C,* vol. 78, pp. 378-391, 2017.

[9] M. Scoble and Y. Muftuoglu, "Derivation of a diggability index for surface mine equipment selection," *Mining Science and Technology,* vol. 1, no. 4, pp. 305-322, 1984.

[10] P. Segarra, J. Sanchidrián, L. López, and E. Querol, "On the prediction of mucking rates in metal ore blasting," *Journal of Mining Science,* vol. 46, no. 2, pp. 167-176, 2010.

[11] T. Kujundžić, M. Klanfar, T. Korman, and Z. Briševac, "Influence of crushed rock properties on the productivity of a hydraulic excavator," *Applied Sciences,* vol. 11, no. 5, p. 2345, 2021.

[12] M. Xing, K. Awuah-Offei, S. Long, and S. Usman, "The effect of local supply chain on regional economic impacts of mining," *The Extractive Industries and Society,* vol. 4, no. 3, pp. 622-629, 2017.

[13] M. S. Dotto and Y. Pourrahimian, "Effects of Fragmentation Size Distribution on Truck-Shovel Productivity."

[14] E. T. Brown, "Rock characterization, testing & monitoring: ISRM suggested methods," 1981.