La productividad en la carga, la resistencia de la roca y la energía del explosivo

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ABSTRACT

Twenty production blasts in two open pit mines were monitored, in rocks with medium to very high strength. Three different blasting agents (ANFO, watergel and emulsion blend) were used, with powder factors ranging between 0.88 and 1.45 kg/m^3. Excavators were front loaders and rope shovels. Mechanical properties of the rock, blasting characteristics and mucking rates were carefully measured. A model for the calculation of the productivity of excavators is developed thereof, in which the production rate results as a product of an ideal, maximum, productivity rate times an operating efficiency. The maximum rate is a function of the dipper capacity and the efficiency is a function of rock density, strength, and explosive energy concentration in the rock. The model is statistically significant and explains up to 92 % of the variance of the production rate measurements.

RESUMEN

Se han analizado veinte voladuras de producción en dos minas a cielo abierto, en rocas con resistencia entre media y muy alta. Se usaron tres agentes de voladura diferentes (ANFO, hidrogel y emulsión mezcla), con consumos específicos entre 0.88 y 1.45 kg/m^3. Las excavadoras eran cargadoras frontales y palas de cables. Se midió cuidadosamente las propiedades de la roca, las características de las voladuras y las velocidades de carga, a partir de las cuales se desarrolla un modelo para el cálculo de la productividad de las excavadoras en el que ésta es función de una productividad máxima o ideal multiplicada por una eficacia operativa. La producción máxima es función de la capacidad del cazo y la eficiencia es función de la densidad y resistencia de la roca, y de la concentración energética del explosivo en la roca. El modelo tiene significación estadística y explica un 92 % de la varianza de las medidas de velocidad.

1. INTRODUCTION

The knowledge of the parameters with a major effect on the production rate of excavating equipment is useful in order to optimize the operation, to achieve a production target or to plan the purchase of new machines. Mining manuals provide loading cycle times or production rates of excavators as function of the volume of the bucket and a qualitative description of the ease of excavation of the rock or its diggability (Sweigard 1998, Atkinson 1998). Kuznetsov et al. (1997) use a measure of rock strength to estimate the diggability of non-blasted rocks. Productivity of excavators has been analyzed from the explosive concentration angle by Eloranta (1995) and McKenzie et al. (1998), with contradictory results and remarkable scatter in the data. Other efforts in this area worth mentioning include the analysis by Brunton et al. (2003) of the influence of the 80 % passing size on the dig time.

Segarra et al. (2010) developed a model of the productivity of excavators as the product of an optimum mucking rate value times an operational efficiency, a function of rock properties, blast design and bucket capacity. In that model, the optimum mucking rate is tied to the efficiency in a site or data-dependent manner, in the sense that the optimum mucking rate does not depend on any scale parameter – such as some variable related with the size of the excavator – as it should obviously do. This paper revises Segarra et al.'s model using the same data, in an attempt to make it more meaningful by incorporating a scale-dependent variable in the maximum mucking rate.

2. MEASUREMENTS AND DATA

Data belong to two Brazilian mines: Conceição (iron) and Sossego (copper). They comprise 20 blasts in rocks with medium to very high strength, with three blasting agents, covering a powder factor span between 0.88 and 1.45 kg/m^3. The excavators used to dig and load the rock were front loaders and rope shovels with nominal bucket payloads of 38, 45.4 and 81.6 tonnes. The trucks capacity was 240 tonnes in all cases.

The levels, rock types and mechanical properties are given in Table 1. The rock samples were taken in the bench so that their strength is probably lower than the in-situ, undisturbed rock. Point load strength is the size-corrected value, $I_{s(50)}$ (ISRM 1985, AENOR 1996).

Table 1. Rock properties.

Mine	Bench	Rock type	Point load strength MPa (*)	Density kg/m^3 (*)
Conceição	820	Hematite	4.8±1.7	3556±576
	955	Itabirite	3.1±1.0	2880
	970	Itabirite	4.0±1.4	3470
	985	Itabirite	5.6±1.0	3725
Sossego	136	Ore	9.3±2.1	3349±212
	168	Waste	7.1±1.3	2814±270
	184	Waste	7.0±2.1	2793±173
	200	Ore	9.4±1.0	3349±212
		Waste	7.0±1.9	2530± 56

(*) Mean and standard deviation.

Table 2. Characteristics of the blasts.

Blast	Bench	Rock	Explosive	q_t, kg/m^3	q, kg/m^3	t_{I-R}, ms	t_R, ms
1	955	Itabirite	Watergel	1.02	0.86	42	100
2	985	Itabirite	Watergel	1.28	1.13	42	100
3	820	Hematite	Watergel	1.03	1.03	42	100
4	955	Itabirite	Watergel	1.09	0.86	42	100
5	985	Itabirite	ANFO	1.01	0.82	Det. cord.	200
6	970	Itabirite	ANFO	0.98	0.90	Det. cord.	200
7	955	Itabirite	ANFO	1.06	0.99	Det. cord.	200
8	985	Itabirite	Watergel	1.31	0.99	42	100
9	970	Itabirite	Emulsion blend	1.45	1.45	42	100
10	970	Itabirite	Watergel	1.00	0.79	42	100
11	970	Itabirite	Watergel	1.17	0.77	42	100
12	200	Ore	Watergel	1.21	1.10	30	75, 100
13	184	Waste	Watergel	1.03	0.88	20, 30	75
14	184	Waste	Watergel	1.11	0.98	20, 30	75
15	200	Waste	Watergel	1.21	1.07	0, 20, 30	100
16	136	Ore	Watergel	1.03	0.95	30	75
17	200	Ore	Watergel	1.05	0.93	20, 30	50, 75
18	184	Waste	Watergel	1.06	0.94	20, 30	50, 75
19	184	Waste	Watergel	1.00	0.88	30	50, 75
20	168	Waste	Watergel	0.88	0.75	30	50, 75

q_t: total powder factor; q: powder factor above grade; t_{I-R}: in-row delays; t_R: inter-rows delays

Table 3. Excavator productivity data.

Blast	Excavator	B_M, t	B_V, m^3	M_T, t	P_T	t_T, min
1	Bucyrus 295	38.0	21	240	6.9±0.3	3.6±0.1
2	CAT 994	38.0	15	240	6.6±0.1	5.7±0.5
3	CAT 994	38.0	15	240	6.9±0.3	4.3±0.7
4	Bucyrus 295	38.0	21	240	6.7±0.5	3.4±0.4
5	CAT 994	38.0	15	240	8.1±0.6	9 ±0.6
6	Bucyrus 295	38.0	21	240	6.9±0.4	7.1±0.6
7	Bucyrus 295	38.0	21	240	6.7±0.5	6.9±0.8
8	CAT 994	38.0	15	240	7.7±0.1	5.9±0.2
9	Bucyrus 295	38.0	21	240	6.0±1.0	6.4±1.1
10	Bucyrus 295	38.0	21	240	5.3±0.7	3.3±0.3
11	Bucyrus 295	38.0	21	240	6.1±0.2	3.9±0.2
12	CAT 994	38.0	15	242±5	8.7±0.6	7.0±0.7
13	P&H 4100	81.6	55	236±8	4.3±0.6	2.5±0.4
14	P&H 2300	45.4	21	234±6	6.7±1.5	4.2±0.9
15	P&H 2300	45.4	21	244±6	6.3±0.6	4.0±0.3
16	P&H 2300	45.4	21	242±8	7.0±1.0	6.6±0.7
17	P&H 2300	45.4	21	244±5	7.3±0.6	5.8±0.4
18	P&H 2300	45.4	21	237±4	6.3±0.6	4.4±0.2
19	P&H 2300	45.4	21	239±8	6.7±0.6	4.5±0.1
20	P&H 2300	45.4	21	241±3	7.0	4.4±0.1

B_M: Bucket payload; B_V: Bucket volume; M_T: mass loaded into the truck; P_T: passes required to load a truck; t_T: truck loading time.

The main characteristics of the blasts are given in Table 2. Additional data are reported in the work by Segarra et al. (2010). Blasts 1 to 11 are Conceição's and 12 to 20 Sossego's. Explosives used were ANFO (three blasts), emulsion/ANFO 70/30 blend (one blast) and watergel (sixteen blasts). The blastholes were bottom-initiated (cast boosters, 450 g in

Conceição and 1000 g in Sossego). Non-electric detonators were used, except blasts 5, 6 and 7, where detonating cord was used in the rows and 200 ms relays inter-rows.

Mucking operations were manually monitored in both mines for about 30 minutes per day during three days following the blast. The excavator and mucking data are shown in Table 3. Truck loads are nominal for Conceição.

3. ANALYSIS AND DISCUSSION

The unit operations of a complete loading cycle are: dig, swing, dump, return swing and bucket spot (Sweigard 1998, Hall 2003). The total time required to fully load a truck, t_T is measured from the first bucket dumping to the last one; this prevents including in this time the non-productive lapse in which the excavator waits for the truck to be in position (Williamson et al. 1983, Brunton et al. 2003) but, at the same time, it brings some inconsistency between the mass loaded onto a truck, M_T, and the actual time for it, since the truck is loaded in P_T passes and the time measured corresponds in fact to P_T -1 passes (see Figure 1). The actual time for a complete truck loading can thus be estimated as $P_T/(P_T-1)\cdot t_T$, and the volume loading rate is (bank cubic meters, BCM, per unit time, Q):

$$Q = \frac{M_T}{\frac{P_T}{P_T - 1}\cdot t_T}\frac{1}{\rho_R} \tag{1}$$

where ρ_R is the bank density of the rock.

For the purpose of establishing a relation between the excavator rate and the characteristics of the rock and the blasting, the rate is assumed to be the product of an ideal (maximum) rate Q^0 times an operating efficiency η:

$$Q = Q^0\eta \tag{2}$$

Q^0 must necessarily depend on some scale parameter such as the dipper capacity. The following forms have been tested:

$$Q^0 = c_1 B_M^{c_2} \tag{3a}$$

$$Q^0 = c_1 B_V^{c_2} \tag{3b}$$

$$Q^0 = c_1 (B_M / \rho_R)^{c_2} \tag{3c}$$

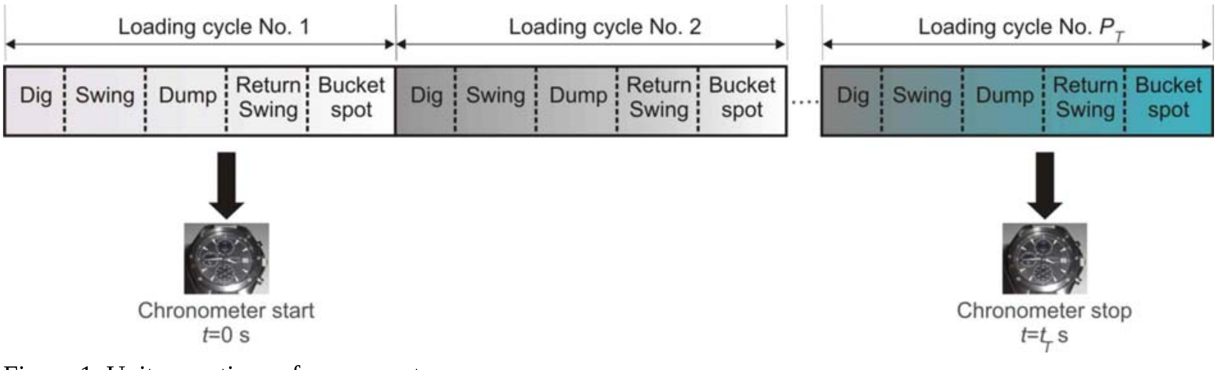

Figure 1. Unit operations of an excavator.

Where B_M and B_V are dipper payload and volume respectively. Type of excavator, truck capacity, excavator/truck matching, loading technique (single or double sided), etc. are also variables influencing the maximum rate (Bohnet 1998) but they are not analyzed in this work.

The efficiency depends, according to previous work (Sweigard 1998, Atkinson 1998), on the dipper capacity and the diggability of the rock. The latter is a function of the rock properties (Sweigard 1998, Atkinson 1998, Awuah-Offei & Frimpong 2007, Chung & Katsabanis 2008) and of the fragmentation and heave achieved by the blast (Williamson et al. 1983, Hendricks et al. 1990, Chung & Preece 1999, Brunton et al. 2003, López-Jimeno et al. 2003, Osanloo & Hekmat 2005, Singh et al. 2005). In order to account separately for the rock characteristics and the blasting effect, the total efficiency η has been split in two components, η_R and η_B:

$$Q = Q^0 \eta_R \eta_B \tag{4}$$

A concept similar to the rock component of the efficiency has been used by Kuznetsov et al. (1997) as follows:

$$\eta_R = e^{-1.6 f_R/(3B_V^{1/2})} \tag{5}$$

Where f_R is the Protodyakonov rock hardness ratio. In the present work, a combination of the two rock properties available, density and strength, has been used in a weighted form taken from Lilly (1986) and the Kuz-Ram model's (Cunningham 1987) density and hardness term of the blastability index:

$$f_R = 0.025\rho_R - 50 + UCS/5 \tag{6}$$

UCS being uniaxial compressive strength (MPa). There are a number of relations to estimate the UCS from the point load value (ISRM 1985, AENOR 1996, Kahraman 2001, Sulukcu & Ulusay, 2001); using the ISRM one, UCS ≈ $22I_{s(50)}$:

$$f_R = 0.025\rho_R - 50 + 4.4I_{S(50)} \tag{7}$$

Figure 2 shows a plot of the rock factor f_R with the density in abscissa and the UCS as parameter of the lines. The points show the data values (Table 1).

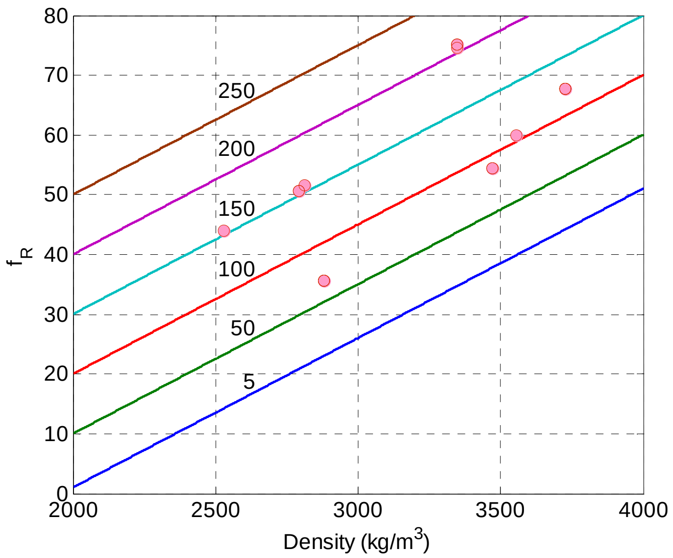

Figure 2. Rock factor. The labels of each line are UCS (MPa).

The dipper volume, as in Equation 5, has turned out to be an irrelevant predictor of the rock part of the mucking efficiency; hence η_R has been formulated simply as:

$$\eta_R = e^{-k f_R} \tag{8}$$

k being a factor to be determined from the data.

The effect of blasting in the mucking productivity has been investigated by a number of authors. The productivity is low at low explosive energy concentration in the rock, since the digging then is hard (López-Jimeno et al. 2003, Swanepoel 2003); as the concentration increases, the material flows more easily, the muckpile becomes flatter and the productivity increases (McKenzie et al. 1998), until a maximum is reached at a critical concentration. Beyond that point no further improvement takes place since the angle of repose of the smaller fragments diminishes and the throw increases, resulting in flatter piles in which more than one pass may be required to fill the bucket (Singh et al. 2005). In order to account for this behavior, a bell-shaped function of the explosive concentration E_E has been used for the blasting component of the efficiency:

$$\eta_B = e^{-\frac{(E_E - E_E^0)^2}{2\sigma^2}} \tag{9}$$

where E_E^0 is the explosive concentration at which the efficiency is maximum, and σ is a shape factor, both to be determined from the data. The value of the critical concentration depends on the rock characteristics (i.e. different energy inputs are required to achieve similar muckpiles in different rocks) and on the loader type (e.g. rope shovels or wheel loaders, Williamson et al. 1983, López-Jimeno et al. 2003, Swanepoel 2003). A dependence of E_E^0 on the rock factor f_R has been tested but no such dependence has been observed from the data used. Other blast design parameters, such as the delay time between rows, have an apparent influence in the muckpile shape (Konya 1995), but they have not been analyzed.

The explosive concentration can be expressed in a variety of ways, the classical and more common one being the mass of explosive per unit volume or unit mass of rock, usually called powder factor. Since rock blasting is a matter of energy delivery in the form of stress waves, the energetic value of the explosive is commonly included in blast design formulae (e.g. Langefors 1963, Cunningham 1983, 1987 and Chung & Katsabanis 2000). Segarra et al. (2008) have reviewed different energy values (heat of explosion, useful work down to several cut-off pressures, and ideal vs. partial reaction models) in the calculation of mucking rates and concluded that the best energy description to fit mucking rate data is the useful work to 100 MPa calculated with a partial reaction model that uses the experimental velocity of the explosive to determine the degree of reaction (Sanchidrián & López 2006). These energies, E_{100}^P, are: ANFO: 987 kJ/kg; emulsion blend: 1621 kJ/kg; watergel: 2147 kJ/kg (Segarra et al. 2008). Energy concentration per unit volume of rock is calculated as the product of these energies times the powder factors in Table 2. Both factors, total and above grade, have been tried, with a better fit obtained using the powder factor above grade, q; this is consistent with the observation that the subdrill has a relatively small influence on the fragmentation (Cunningham 1983), the rock movement (Sanchidrián et al. 2005) and the muckpile shape (Chiappetta & Mammele 1987). The energy concentration or energy powder factor is, then:

$$E_E = qE_{100}^P \tag{10}$$

Replacing (8) and (9) in (4):

$$Q = Q^0(c_1, c_2)\, e^{-k f_R} e^{-\frac{(E_E - E_E^0)^2}{2\sigma^2}} \tag{11}$$

The three forms in Equation 3 have been tried for Q^0. The coefficients c_1, c_2, k, e_E^0 and σ have been determined from the data in Tables 1 to 3 by a non-linear least squares fit using a reflective Newton method (Coleman & Li 1994, 1996) to minimize the sum of squares; the programming has been done in Matlab. The results are given in Table 4 for the three Q^0 forms. The units of the variables are Q, m^3/h (BCM/h); B_V, m^3;B_M, tonnes; ρ_R, kg/m^3; f_R, calculated from Equation 6, with rock density kg/m^3 and point load strength MPa; E_E, kJ/m^3.

The determination coefficient is also given in Table 4. The results are of similar quality for the three forms of Q^0, with slightly better result for the one in Equation 3a. With this, the model is, finally:

$$Q = c_1 {B_M}^{c_2} e^{-k f_R} e^{-\frac{(E_E - E_E^0)^2}{2\sigma^2}} \tag{12}$$

The coefficients are all significant at a 95 % level, as the p-values lower than 0.05 tell. However, it should be pointed out that the leading factor, c_1, is the least significant one, meaning that the ideal mucking capacity of the excavator should probably require a model with more parameters than the dipper capacity alone. The ideal mucking capacity Q^0 ranges from about 2000 to 4000 BCM/h. The optimum energy factor is consistently close to 1900 kJ/m^3.

Figure 3 shows the plot of measured vs. calculated values. The slope of the linear fit is close to unity; the residuals are normally distributed as from the Lilliefors test, and homoscedastic as from Engle’s Lagrange multiplier test.

Figure 4 shows the rock and the blasting components of the efficiency, η_R, a function of the rock factor (Equation 8), and η_B, a function of the energy powder factor (Equation 9). The total efficiency, η, is plotted in Figure 5. Circles in Figures 4 and 5 show the location of the data.

Table 4. Parameters of the models and determination coefficients.

	$Q^0 = c_1 B_M^{c_2}$		$Q^0 = c_1 B_V^{c_2}$		$Q^0 = c_1 (B_M / \rho_R)^{c_2}$	
Coefficients	Mean	p-value	Mean	p-value	Mean	p-value
c_1	223.6	0.027	592.1	0.017	20882	0.018
c_2	0.656	2×10^{-5}	0.450	6×10^{-4}	0.531	3×10^{-5}
k	0.0189	1×10^{-5}	0.0180	3×10^{-5}	0.0152	3×10^{-5}
E_E^0	1878	$<1\times10^{-6}$	1884	$<1\times10^{-6}$	1853	$<1\times10^{-6}$
σ	868	$<1\times10^{-6}$	883	9×10^{-6}	861	$<1\times10^{-6}$
R^2	0.917		0.877		0.913	

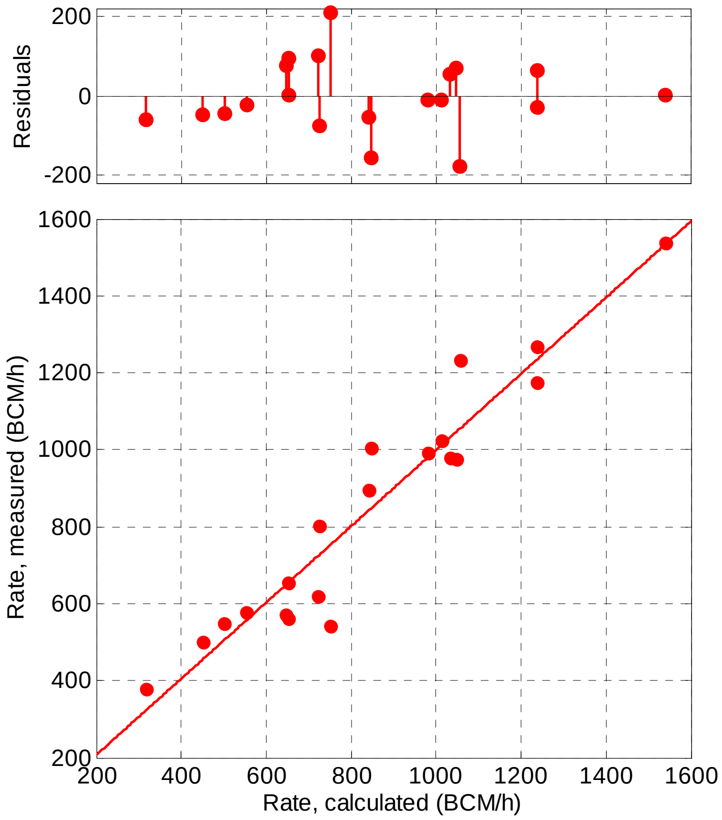

Figure 3. Production rates measured and predicted by the model.

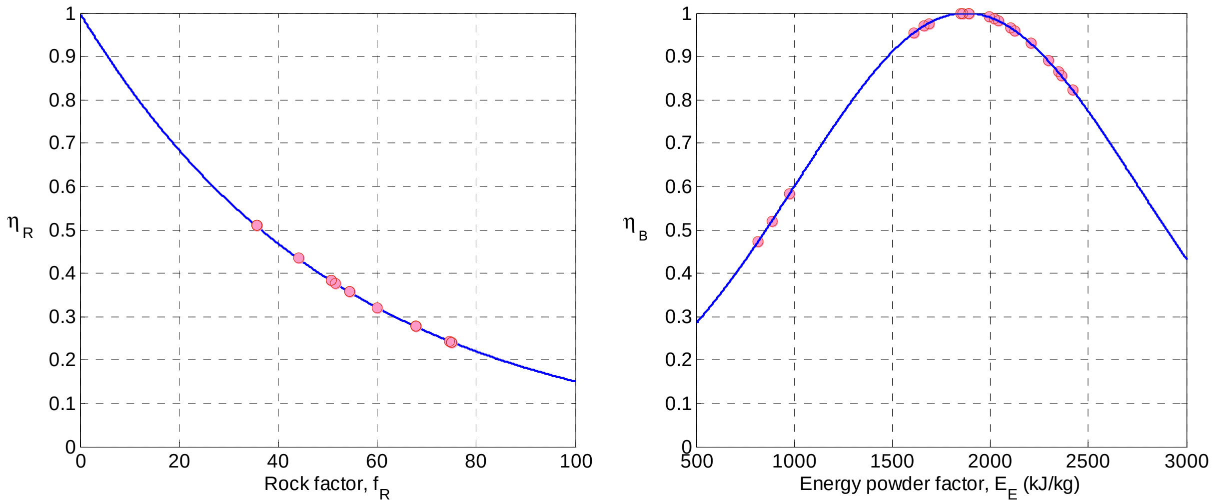

Figure 4. Components of the mucking efficiency. Left: rock; right: blast.

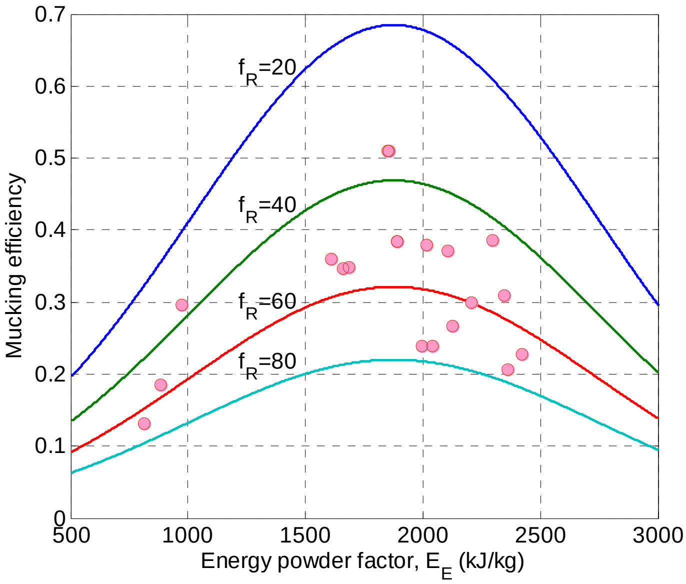

Figure 5. Mucking efficiency.

4. CONCLUSIONS

The production rate of the excavators is a good indicator of the performance of a blast. Such rate can be easily determined, with acceptable accuracy, either manually or from dispatch data. A model has been developed to estimate the mucking production rate in bank cubic meters per hour, as the product of an ideal, maximum rate, times an efficiency that accounts for the rock strength and the energetic powder factor.

The rock strength term of the efficiency uses a factor that combines density and strength in the same way as the Lilly/Kuz-Ram blastability index. The blasting term of the efficiency is a bell-shaped function of the energetic powder factor.

The model has been fit to rock, blasting and loader productivity data of twenty blasts in two, iron and copper, mines. Mucking rates ranged from 378 to 1537 BCM/h; point load strength of the rock ranged from 3.1 to 9.4 MPa and density from 2530 to 3556 kg/m^3. ANFO, emulsion blend and watergel blasting agents were used with powder factors from 0.88 to 1.45 kg/m^3. Excavators in the blasts monitored were rope shovel excavators and front wheel loaders with nominal payloads between 38 and 81.6 tonnes; truck capacity was 240 tonnes. The model explains 92 % of the variance of the production rate and is statistically significant.

The ideal, maximum productivity has been modeled as a function of the nominal dipper payload; additional data should help to include the effect of variables such as rock strength and loader type in the model.

The explosive energy value that has shown to better explain the influence of the blast on the mucking rates is the useful expansion work down to 100 MPa, obtained from a non-ideal detonation point meeting the experimental detonation velocity. The efficiency is maximum at an optimum value of the energy powder factor close to 1900 kJ/kg. No general claim is made on that figure; on the contrary, a relationship must exist between the optimum energy powder factor and the rock strength, though this has not been found with the limited variability of the data used.

5. ACKNOWLEDGEMENT

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6. REFERENCES

AENOR, *Propiedades mecánicas de las rocas. Ensayos para la determinación de la resistencia. Parte 5: Resistencia a carga puntual (Norma UNE 22950-5).* Madrid: Asociación Española de Normalización y Certificación (1996). In Spanish.

Atkinson, T., Selection and sizing of excavating equipment, in: Hartman H.L. (ed.) *SME mining engineering handbook on CD-Rom*, Colorado: Society for Mining, Metallurgy and Exploration, Inc. (1998).

Awuah-Offei, K. & Frimpong, S., Cable shovel digging optimization for energy efficiency, *Mechanism and Machine Theory* 42-8:995-1006 (2007).

Bohnet, E.P., Method advantages and disadvantages, in: Hartman H.L. (ed.) *SME mining engineering handbook on CD-Rom*, Colorado: Society for Mining, Metallurgy and Exploration, Inc. (1998).

Brunton, I., Thornton, D., Hodson, R. & Sprott, D., Impact of blast fragmentation on hydraulic excavator dig time, *Proc. of the 5th Large Open Pit Conf.*, Kalgoorlie, Australia (2003).

Chiappetta, R.F. & Mammele, M.E., Analytical high-speed photography to evaluate air decks, stemming retention and gas confinement in presplitting, reclamation and gross motion applications, *Proc. of the 2nd Int. Symp. on Rock Fragmentation by Blasting*, Keystone, Colorado (1987).

Chung, S.H. & Katsabanis, P.D., Fragmentation prediction using improved engineering formulae, *Int. J. for Blasting and Fragmentation*, 4-3/4:198-207 (2000).

Chung, S.H. & Katsabanis, P.D., A discrete element code for diggability analysis, *Proc. of the 34th Annual Conf. on Explosives and Blasting Technique*, New Orleans, Louisiana (2008).

Chung, S.H. & Preece, D.S., Explosive energy and muckpile diggability, *Proc. of the 25th Annual Conf. on Explosives and Blasting Technique*, Nashville, Tennessee (1999).

Coleman, T.F. & Li, Y., On the convergence of reflective Newton methods for large-scale nonlinear minimization subject to bounds, *Mathematical Programming* 67-2:189-224, 1994.

Coleman, T.F. & Li, Y., An interior, trust region approach for nonlinear minimization subject to bounds, *SIAM Journal on Optimization* 6:418–445, 1996.

Cunningham, C.V.B., The Kuz-Ram model for prediction of fragmentation from blasting, *Proc. of the 1st Int. Symp. on Rock Fragmentation by Blasting*, Luleå, Sweden (1983).

Cunningham, C.V.B., Fragmentation estimations and the Kuz-Ram model - four years on, *Proc. of the 2nd Int. Symp. on Rock Fragmentation by Blasting*, Keystone, Colorado (1987).

Eloranta, J., Selection of powder factor in large diameter blastholes, *Proc. of the Explo'95 - Exploring the role of rock breakage in mining and quarrying*, Brisbane, Australia (1995).

Hall, A., Characterizing the operation of a large hydraulic excavator, *Master's thesis*, Brisbane: The University of Queensland (2003).

Hendricks, C., Peck, J. & Scoble, M., Integrated drill and shovel performance monitoring towards blast optimization, *Proc. of the 3rd Int. Symp. on Rock Fragmentation by Blasting*, Brisbane, Australia (1990).

ISRM, Suggested method for determining point load strength, J.A. Franklin (working group co-coordinator), *Int. J. of Rock Mech. Min. Sci. & Geomech. Abst*r. 22-2:53-69 (1985).

Kahraman, S., Evaluation of simple methods for assessing the uniaxial compressive strength of rock, *Int. J. Rock Mech. Min. Sci.* 38-7:981-994 (2001).

Konya, C.K., *Blast design*, Montville: Intercontinental Development Corporation (1995).

Kuznetsov, V.I., Mattis, A.R., Tashkinov, A.S., Vasil'ev, E.I. & Zaytsev, G.D., Efficiency of excavation of overburden rock at quarries with the use of blast-free technology, *Journal of Mining Science* 33-5:471-477 (1997).

Langefors, U. & Kihlström, B., *The Modern Technique of Rock Blasting*, New York: John Wiley and Sons, 1963.

Lilly, P., An empirical method of assessing rock mass blastability, *Proc. of the AusIMM/IE Aust Newman Combined Group Large Open Pit Mining Conf.*, Newman, Australia, October 1986, pp. 89-92. Melbourne: The AusIMM.

López-Jimeno, C., López-Jimeno, E. & García-Bermúdez, P., *Manual de perforación y voladura de rocas* Madrid (2003). In Spanish.

McKenzie, C.K., Geddes, P., Grohs, K. & Morrish, M., Blasting trials to control and monitor displacement of narrow vein gold ore, *Proc. of the 24th Annual Conf. on Explosives and Blasting Technique*, New Orleans, Louisiana (1998).

Osanloo, M. & Hekmat, A., Prediction of shovel productivity in the Gol-e-Gohar iron mine, *Journal of Mining Science* 41-2:177-184 (2005).

Sanchidrián, J.A. & López, L.M., Calculation of the energy of explosives with a partial reaction model, *Propellants Explosives Pyrotechnics*, 31-1:25-32 (2006).

Sanchidrián, J.A., Segarra, P. & López, L.M., On the relation of rock face response time and initial velocity with blasting parameters, *Proc. of the 3rd EFEE Conf. on Explosives and Blasting*, Brighton, U.K. (2005).

Segarra, P., Sanchidrián, J.A., Montoro, J.J. & López, L.M., Mucking efficiency in open pit blasting, *CIM Bulletin Technical Papers 2007 (transactions volume)*:246-256 (2008).

Segarra, P., Sanchidrián, J.A., López, L.M. & Querol, E., On the prediction of mucking rates in metal ore blasting, *Journal of Mining Science* 46-2:167-176 (2010).

Singh, S.P., Narendrula, R. & Duffy, D., Influence of blasted muck on the performance of loading equipment, Proc. *3rd EFEE Conf. on Explosives and Blasting*, Brighton, U.K. (2005).

Sulukcu, S. & Ulusay, R., Evaluation of the block punch index test with particular reference to the size effect, failure mechanism and its effectiveness in predicting rock strength, *Int. J. Rock Mech. Min. Sci.* 38-8:1091-1111 (2001).

Swanepoel, W., The influence of bench height and equipment selection on effective mineral resource utilization, Thesis (M. Eng.), Pretoria: University of Pretoria (2003).

Sweigard, R.J., Materials handling: loading and haulage, in: Hartman H.L. (ed.) *SME mining engineering handbook on CD-Rom*, Colorado: Society for Mining, Metallurgy and Exploration, Inc. (1998).

Williamson, S., McKenzie, C. & O'Loughlin, H., Electric shovel performance as a measure of blasting efficiency, *Proc. of the 1st Int. Symp. on Rock Fragmentation by Blasting*, Luleå, Sweden (1983).