MODELING IRON ORE DEGRADATION DURING HANDLING[1]

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Abstract

Degradation of iron ore during handling causes a significant economic impact, given the higher prices achieved by lump ore in comparison to finer products. Prediction of the amenability of iron ores to degradation is relevant, since it can be used to investigate the response of ores to different sequences of handling and transportation events from mine to port, which, in turn, is a useful tool to assess the effectiveness of actions taken to minimize this effect. The paper presents a fundamental model to describe degradation caused by transfers and drops of the particulate material. It is based on data collected from drop tests, drop weight tests and tumbling tests and on description based on damage mechanics in addition to distribution of strengths of the original material. This model is capable of predicting the proportion of particles broken and the entire size distribution resulting from any sequence of impact events. The model has been validated using data from self-breakage of a Brazilian iron ore and used in simulations of the influence of different sequences of impact on lump ores from different sources.

Key words: Iron ore; Degradation; Particle breakage.

MODELAGEM DA DEGRADAÇÃO DE MINÉRIO DE FERRO DURANTE O MANUSEIO

Resumo

A degradação de minério de ferro durante o transporte tem um impacto econômico significativo, tendo em vista os maiores preços alcançados pelos produtos granulados em comparações aos mais finos. A previsão da suscetibilidade de minérios de ferro à degradação é relevante, uma vez que pode ser usada para investigar a resposta de produtos granulados a diferentes seqüências de eventos de manuseio e transporte da mina até o porto, a qual, por sua vez, é uma ferramenta útil na avaliação da eficácia de medidas tomadas para minimizar esse efeito. O artigo apresenta um modelo fundamental para descrever a degradação causada por transferências e quedas de materiais particulados. O modelo é baseado em dados coletados de ensaios de impacto, queda de peso e tamboramento, uma descrição do enfraquecimento do material com base na mecânica do dano, além da distribuição de resistências do material inicial. Este modelo é capaz de prever a proporção de partículas quebradas e a distribuição de tamanhos de partículas a partir de qualquer seqüência de eventos, tendo sido validado a partir de dados de um minério de ferro brasileiro e usado na simulação da influência de diferentes seqüências de impactos aplicados a granulados de procedências variadas.

Palavras-chave: Minério de ferro; Degradação; Quebra de partículas.

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1 INTRODUCTION

Iron ore undergoes significant degradation during mining as a result of blasting, mechanical handling by shovels and then crushing in order to produce a size distribution that is capable of meeting specifications that are set by customers. Whenever a mine is capable of producing competent iron ore lumps that can be loaded directly into a blast-furnace, the mined material is screened and sold as particles contained in the size range typically from 30 to 6.4 mm. Fines comprising the material passing the 6.4 mm sieve cannot be charged directly into the blast-furnace and must first be prepared by agglomeration (typically sintering) to produce suitable lumpy blast-furnace feed.

Degradation of lump ore into fines is undesirable because lumps have premium prices when compared to fines. However, the relationship between the proportion of lump ore and fines that is produced in a given processing plant is co-determined by the ore's mechanical strength and the nature of the crushing and handling processes.[1] In addition to that, between the mine and end user, lump material is subject to a number of mechanical actions which cause degradation. These include: at the mine site – crushing and screening, conveying, stockpiling and rail wagon loading; at the port – rail wagon unloading, conveying, drops at transfer points, screening, stockpiling, reclaiming and ship loading.[2]

Prediction of the amenability of iron ores to degradation is relevant, since it can be used to investigate the response of ores to different sequences of handling and transportation events from mine to port, which, in turn, is a useful tool to assess the effectiveness of actions taken to minimize this effect. A number of attempts have been made in the last few decades to describe quantitatively this phenomenon, with variable results.[2-7] The paper presents a fundamental simulation procedure that describes degradation caused by transfers and drops of the particulate material. It is based on data collected from drop tests, drop weight tests and tumbling tests, a model from damage mechanics and the distribution of strengths in the original material.

2 MODEL DESCRIPTION

When a particle is dropped during a transfer, it may break or not. Whenever the particle does not break catastrophically, its surface will be abraded and it may accumulate crack-like damage and become weakened, so that will eventually break at a comparatively low impact energy in a future drop. Modeling weakening that the particle undergoes after repeated impacts is of major importance to describe degradation during handling, and a model has been proposed to describe it using elements from continuum damage mechanics.[8,9] This model is based on the recognition that the load-deformation response that results from impact of a spherical particle can be described by a combination of continuum damage mechanics [10] and Hertz contact theory [11], giving

$$F = \frac{d^{1/2}}{3} \tilde{k} \ \alpha^{3/2} \tag{1}$$

where F is the load, d the particle size, α is the deformation and

$$\tilde{k} = k(1 - D) \tag{2}$$

is the stiffness of the particle, with $k = Y/(1-\mu^2)$, where Y is the modulus of elasticity and μ the Poisson ratio.

The damage variable D may be described by the power law relationship

$$D = \left(\frac{\alpha}{\alpha_c}\right)^{\gamma} \tag{3}$$

which is valid during compression of the particle. By definition, damage is irreversible,[10] so that, if during compression the particle does not fracture, then during restitution $D = D^*$, where D^* is the maximum value that the damage variable assumed during the loading part of the cycle.

Assuming that the particle orientation and that the model parameters α_c and γ remain constant, Eqs. (1) to (3) can be used successively to predict the force-deformation curves resulting from repeatedly loading of a particle up to a given strain energy level, until failure occurs (Figure 1). Unfortunately, this procedure cannot be easily used in practice because it requires the knowledge of several material constants, including α_c, k, d, besides the damage accumulation coefficient γ. These are material-specific constants that are not easy to determine experimentally.[11] Typically, only the distribution of fracture energies (or the fracture probability distribution) of the original material may be known, using, for example, the impact load cell,[12] besides the stressing energies in each event. A convenient procedure that allows simulating multiple loading events using a limited amount of data has been proposed and is presented elsewhere,[8,13] Assuming that the constitutive equation (Eq. (1)) remains valid throughout the several loading events, the distribution of particle fracture energies after an nth loading is given by[13]

$$F_{n+1}(E) = \left[\frac{F_n\left[E/(1-D)\right] - F_n(E_k)}{1 - F_n(E_k)}\right] \tag{4}$$

$$D = \left[\frac{2\gamma(1-D)}{(2\gamma - 5D + 5)}\frac{E_k}{E}\right]^{\frac{2\gamma}{5}} \tag{5}$$

where $F_n(E_k)$ is the proportion of particles broken in the nth drop from a specific impact energy of E_k. Equation (5) should be solved using an efficient numerical procedure.

Results of experiments used to determine the parameter γ are shown in Figure 2, where the fraction of broken (those that lost at least 10% of their original weight) particles is presented as a function of number of drops, along with model predictions.

In order to simulate degradation during handling, it is necessary to predict the complete size distribution of the material after the drops, not only the cumulative broken. The mass balance of an individual size fraction after each drop of the particles may be represented by

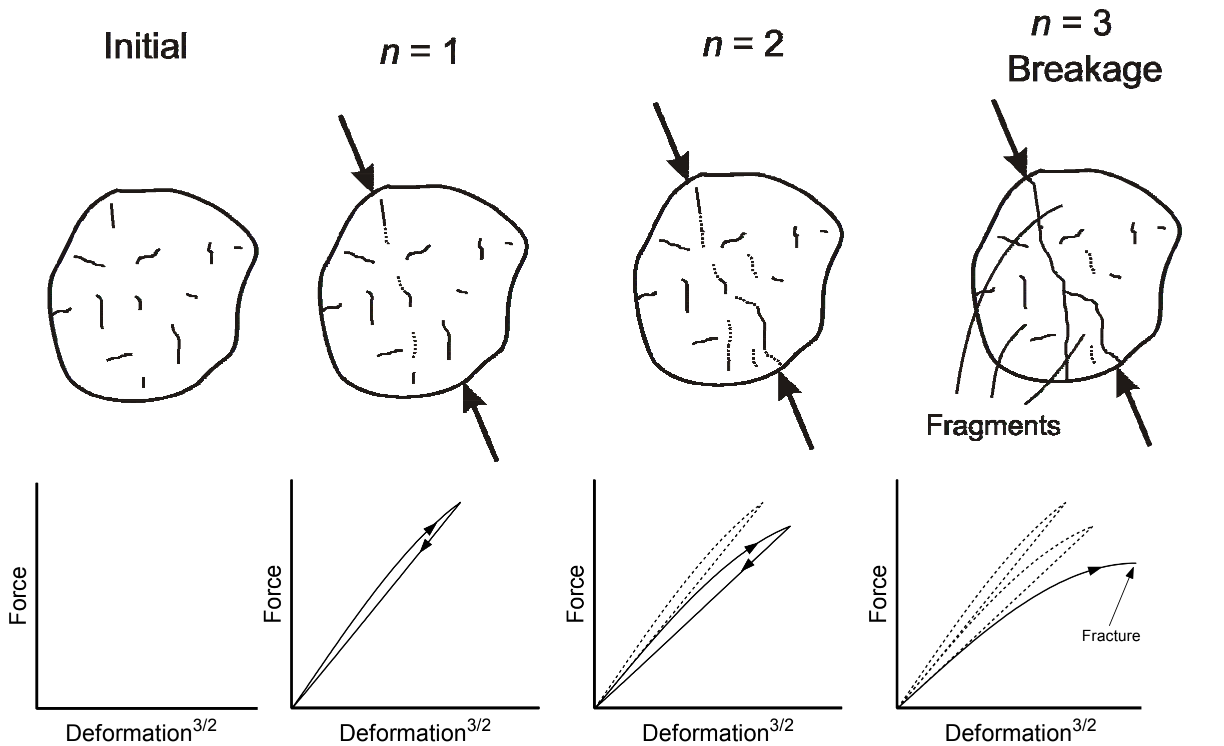

Figure 1. Illustration of the effect of weakening due to accrual of damage in repeated loading events.

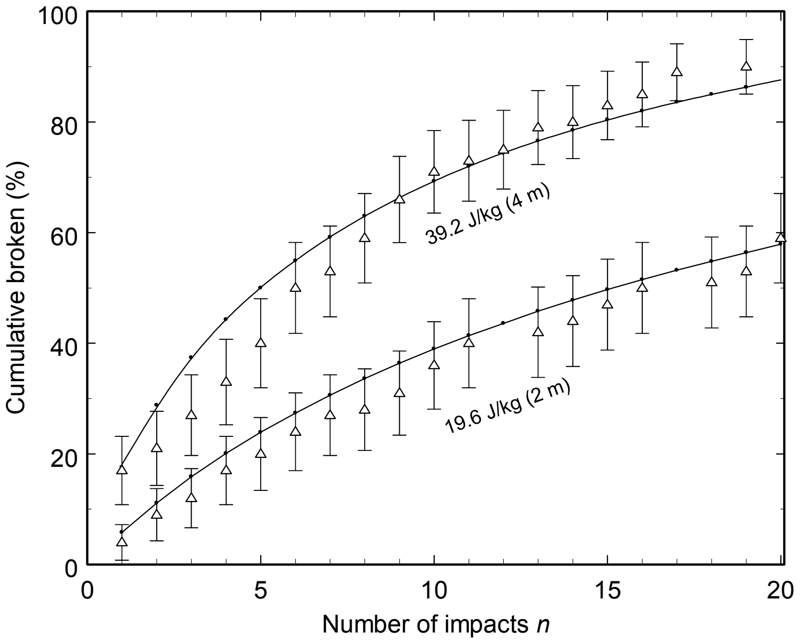

Figure 2. Experimental (triangles) and predicted (small circles and lines) showing the cumulative percentage broken after repeated single impacts at two drop heights of a Brazilian bauxite ore contained in size range 45.0-37.5 mm (γ = 3.7) against a steel plate. Error bars represent the 90% confidence intervals.

$$w_{i,m+1} = w_{i,n}\left[1 - F_{i,n}(eE_{k,n})\right]\left(1-\kappa_j\right) + \sum_{j=1}^{i} w_{j,n}\left[F_{j,n}(eE_{k,n})b_{ij} + \kappa_j\left[1 - F_{j,n}(eE_{k,n})\right]a_{ij}\right] \tag{6}$$

where $w_{i,n+1}$ and $w_{i,n}$ are the weight fraction of the material contained in size class i before and after the nth drop and e is the fraction of the collision energy that is captured by individual particles during a stressing event. $F_{i,n}(eE_k)$ is the probability that a particle contained in size class i will break when it captures energy eE_k from a drop. κ_i is the abrasion rate of particles contained in size class i, which is assumed to be independent of drop height, and $a_{i,j}$ is the abrasion breakage function, given in its cumulative form by[14]

$$A_{i,j} = A_i = \left(\frac{d_i}{d_A}\right)^{\lambda} \tag{7}$$

where d_A and λ are material parameters.

E_k is the specific impact energy which, considering free-fall, is given by

$$E_k = g\,h \tag{8}$$

where g is the acceleration due to gravity and h is the drop height.

The fraction of the impact energy that is captured by a particle when it drops depends both on the characteristics of the particles and the surface. It may be estimated on the basis of Hertz contact theory, which, considering an elastic impact, gives[15]

$$e = \left(\frac{k_{surface}}{k_{surface} + k}\right)\left(\frac{k_{steel} + k}{k_{steel}}\right) \tag{9}$$

where k_{steel} is the stiffness of steel (about 230 GPa). This parameter allows simulating impacts of particles against a steel plate or against other particles. In the later case it becomes $e = 0.5(k_{steel} + k)/k_{steel}$.

The impact-breakage function $b_{i,j}$ is calculated on the basis of the parameter t_{10}, which is calculated from[9]

$$t_{10i} = A\left[1 - \exp\left(-\frac{b' e E_{k,n}}{E_{50bi}}\right)\right] \tag{10}$$

where $E_{k,n}$ is the impact energy and E_{50bi} is the median fracture energy of the particles that broke, which is given by[9]

$$E_{50bi} = F^{-1}\left[\frac{1}{2}F_{i,n}(E_{k,n})\right] \tag{11}$$

The entire breakage function is then calculated on the basis of interpolating data on t_{10} versus the various $t_n s$ using incomplete beta functions.

The initial distribution of particle fracture energies can be generally well described using the log-normal distribution,[12] given by

$$F_{i,0}(E) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\ln E - \ln E_{50i}}{\sqrt{2\sigma_i^2}}\right)\right] \tag{12}$$

with

$$E_{50i} = E_{\infty}\left[1 + \left(\frac{d_o}{d_i}\right)^{\phi}\right] \tag{13}$$

where d_i is the representative size of particles contained in the ith class, σ_i^2 is the variance of the distribution and E_{∞}, d_o and ϕ are model parameters that should be fitted to experimental data.

After each impact, the distribution of fracture energies of particles contained in size class i is given by

$$F_{i,n+1}(E) = \frac{\left[F^*_{i,n+1}(E)w_{i,n}\left(1 - F_{i,n}(E_{k,n})\right)(1-\kappa_i) + F_{i,0}(E)\sum_{j=1}^{i} w_{j,n}\left[F_{j,n}(E_{k,n})b_{i,j} + \left(1 - F_{j,n}(E_{k,n})\right)\kappa_j a_{i,j}\right]\right]}{w_{i,n+1}} \tag{14}$$

where the distribution of particle fracture energies of the particles that were damaged is given by rewriting Equations (4) and (5), so that

$$F^*_{i,n+1}(E) = \left[\frac{F_{i,n}\left[E/(1-D)\right] - F_{i,n}(eE_k)}{1 - F_{i,n}(eE_k)}\right] \tag{15}$$

$$D = \left[\frac{2\gamma(1-D)}{(2\gamma - 5D + 5)}\frac{eE_k}{E}\right]^{\frac{2\gamma}{5}} \tag{16}$$

As presented, the model is predictive and does not require fitting parameters to calculate the response from multiple drops. However, it relies on data from carefully conducted experiments in the impact load cell and also on data from a single drop test at different number of drops. These data are obtained as follows.

3 MATERIAL AND METHODS

Samples from three iron ores (a Brazilian itabirite – IO1, a Canadian ore – IO2 and a North American taconite – IO3) were collected. Sample preparation consisted of classifying particles into a range of particle sizes. These narrow size fractions were subjected to single-particle impact-breakage tests in the impact load cell and tumbling tests in order to determine the material parameters required for simulation and then to drop tests for model validation.

The impact load cell is a drop weight tester which consists of a long rod onto which solid-state strain gauges are attached.[12] The experiment consisted of impacting individual particles with a free-falling drop weight and recording the force-time profile. From the force-time profile the specific particle fracture energy E of individual particles and the particle stiffness k are calculated. From testing several particles the distribution parameters may be determined from Equation (12). From testing particles contained in different size ranges the parameters in Equation (3) are estimated. In addition, particles contained in these size ranges are impacted at variable energy inputs and their fragment size distribution determined, so that parameters in Equation (10) are estimated, as well as the relationship between the various t_{10} and t_n values. Repeated impacts at a constant impact energy were conducted in the impact load cell for particles contained in a narrow size range and the damage accumulation parameter γ was determined from Equations (4) and (5). Details on the experimental procedure and equipment may be found elsewhere.[9,12]

Abrasion breakage parameters (κ, λ and d_A from Equations 6 and 7) were determined from tumbling loads of 3 kg contained in size range 53.0-37.5 mm in a mill measuring 30x30 cm at 53 rpm in the absence of grinding media. Details of the experimental procedure and data processing may be found elsewhere.[16]

Finally, drop tests used for model validation were conducted by dropping by hand particles of IO1 contained in size range 125-63 mm on a hard metal plate from drop heights of 2 and 4 m. After each impact, fragments were collected and sieved.

4 RESULTS AND DISCUSSION

A summary of model parameters of the ores IO1, IO2 and IO3, determined from single-particle impact-breakage and abrasion breakage tests, is presented in Table 1. The model has been validated using data from drop tests in the laboratory, where lots containing 20 particles of IO1 were dropped against a hard metal plate and the size distribution of the fragments measured. In this test, only the coarsest fragment that continued in the original size range was impacted over again. Figure 3 compares experimental results to predictions of the proportion of -6.4 mm generated after impacts at different drop heights. Agreement between model and experiments was reasonable, if one considers the likely high variability of the data, given the small number of particles subjected to the drop tests. Still, a refinement of the fit may also be possible by calibrating the breakage function (t_{10} versus t_n relationship) using data from drop tests, but this will be the subject of a future publication.

Table 1. Summary of iron ore characteristics determined experimentally and used in the simulations (values in italics are those not determined directly on the samples, but taken from other materials with similar characteristics)

	Impact breakage								Abrasion breakage		
	Eqs. (9, 12-13)					Eq. (10)		Eq. (5)	Eqs. (6-7)		
Iron ore	E_∞ (J/kg)	d_o (mm)	ϕ (-)	σ_i (-)	k (GPa)	A (%)	b' (-)	γ (-)	κ (%)	λ (-)	d_A (mm)
IO1	16.8	20.1	0.84	1.01	12.5	44.2	0.0288	4.9	0.015	0.31	0.25
IO2	47.3	1.08	2.3	0.75	11.5	65.4	0.0932	4.8	*0.023*	*2.1*	*0.30*
IO3	163.3	0.86	1.8	0.77	13.2	*51.0*	*0.0269*	*7.5*	*0.010*	*0.42*	*0.25*

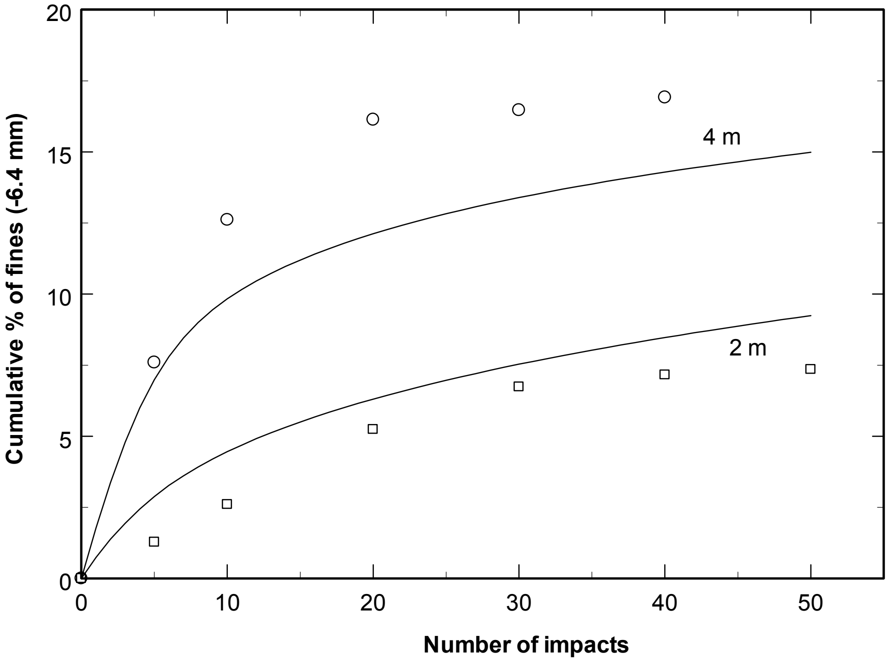

Figure 3. Experimental (symbols) and predicted (lines) results showing the proportion of fines (-6.4 mm material) after repeated single impacts at two drop heights of IO1 contained in size range 125-63 mm against a steel surface.

In order to demonstrate the application of the model to predict lump iron ore degradation during handling, it is assumed that the lump ore, as-produced, has the size distribution given in Table 2. This is the average size distribution found for lump ores currently produced in the Quadrilátero Region of Minas Gerais.[17]

Figure 4 compares the amenability of the different materials to degradation. It is first evident that few fines are produced from repeated drops of IO3 in comparison to IO1 and IO2. The figure also shows that the model response varies, although modestly, as a function of material, in spite of the similarities in several parameters of the IO1 and IO2 studied (Table 1).

Figure 4 also shows the influence of number of impacts and impact surface on the proportion of fines produced. Simulations are presented for IO1 when individual particles impact a steel plate ($k_{surface}$ = k_{steel}) and when they impact a particle bed, such as when they hit against particles resting on a stockpile ($k_{surface}$ = k). Results are consistent with data from Sahoo,[2] which demonstrated that by changing from steel to an ore surface the proportion of fines generated after repeated drops of an Australian iron ore reduced in about half, as long as the proportion of fines was below about 10%, thus preventing the cushioning effect.

Table 2. Size distribution of the lump ore used in the simulations.[17]

Sieve size (mm)	37.5	31.5	25.0	19.0	12.5	9.5	8.0	6.3
Passing (%)	99.1	95.2	74.1	43.9	20.3	10.1	4.4	0.01

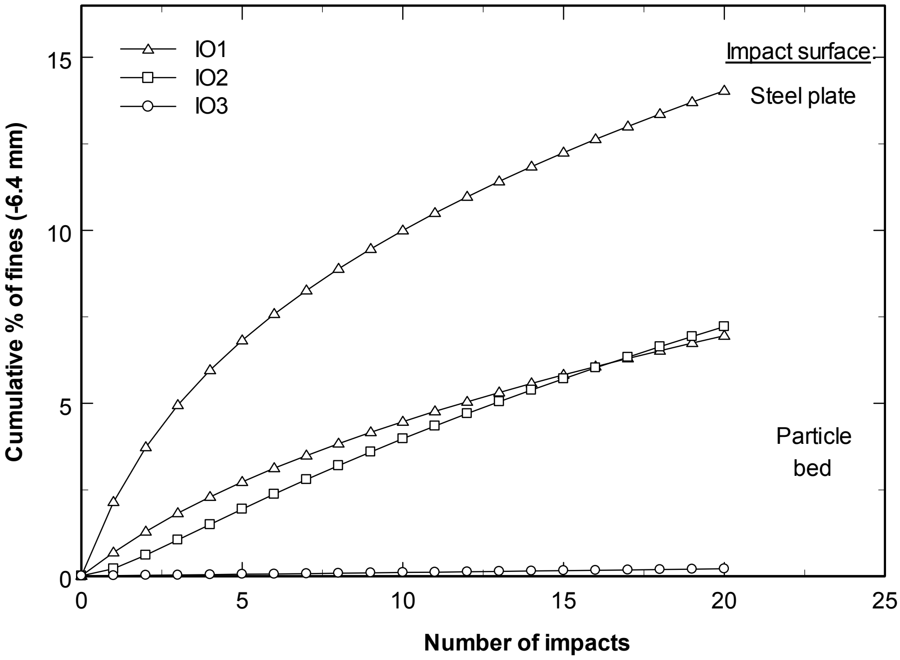

Figure 4. Simulations showing the proportion of fines (-6.4 mm material) after repeated impacts of the different lump ores at a drop heights of 2 m.

The influence of drop height on degradation is investigated in detail in Figure 5, which compares the generation of fines after impacts at different heights, all totaling 30 m (1 x 30 m, 2 x 15 m, 3 x 10 m, …), as used by Norgate et al.[3] in their experiments. The figure shows that degradation can be reduced significantly by using drops below about 1 m or so, which is consistent with observations by Walters and Mika [18], Norgate et al. [3] and Sahoo et al. [20]. Further, Figure 5 also shows that there is an optimum drop height below which abrasion becomes significant. Further, some of researchers cited also recognized that drop heights above 3 m are generally very detrimental in the degradation of iron ores, which is also evident in the figure.

It has been recognized by a number of authors,[4,19-21] that subjecting particles to repeated drops results in the phenomenon called stabilization, that is, since the weakest particles are disintegrated more rapidly, the remaining material becomes tougher (on average) than the original ore. This is illustrated in Figure 6, which shows simulation results on the variation of the median particle fracture energy (E_{50}) for 19 mm particles as a function of number of impacts. It demonstrates that the material "gained strength" upon handling. In practice what happens is that as the weakest particles as broken only the toughest particles, although weakened, are left in the sample.

Some authors[3] have recognized that degradation also depends on the sequence of impact events. They observed that a drop height of a given value will cause more degradation earlier in the handling system rather than later because of conditioning of the ore, removing the weaker particles, although the difference reported was relatively small (1-2%). Simulations have been conducted by dropping lumps of IO1 following two different sequences: in the first case particles were dropped from 20 m and then 9 times from a 1 m height, yielding 13.9% of fines; in the second case the sequence of impacts was inverted, yielding 12.5% of fines. It confirms observations by Norgate et al.,[3] even quantitatively (1.4% difference), which proves that the model is able to account for the physical phenomena involved in degradation during handling.

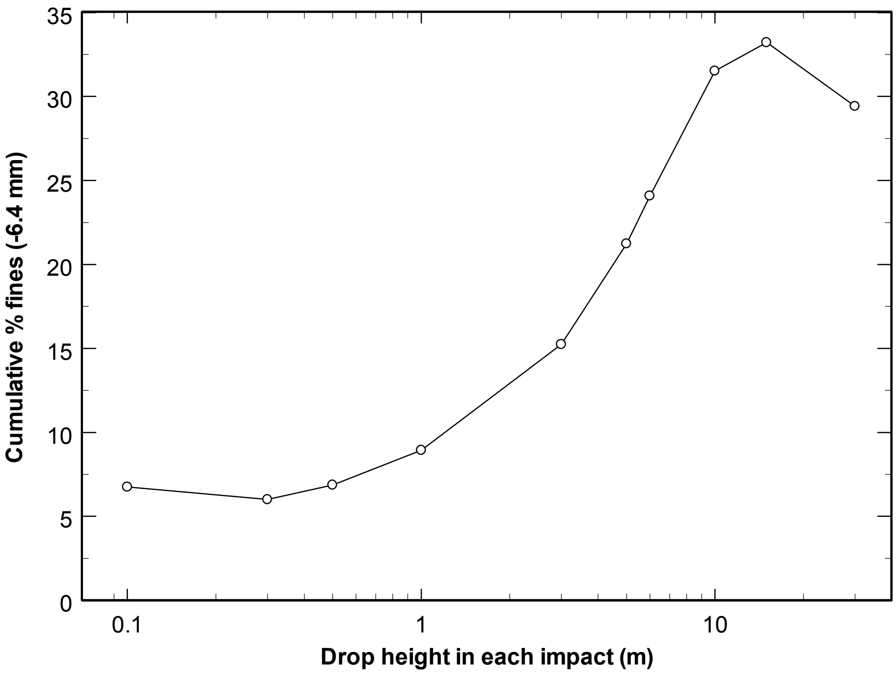

Figure 5. Simulations showing the proportion of fines (-6.4 mm material) after repeated impacts of lump ore IO1 against other particles for different constant drop heights for a total drop height of 30 m.

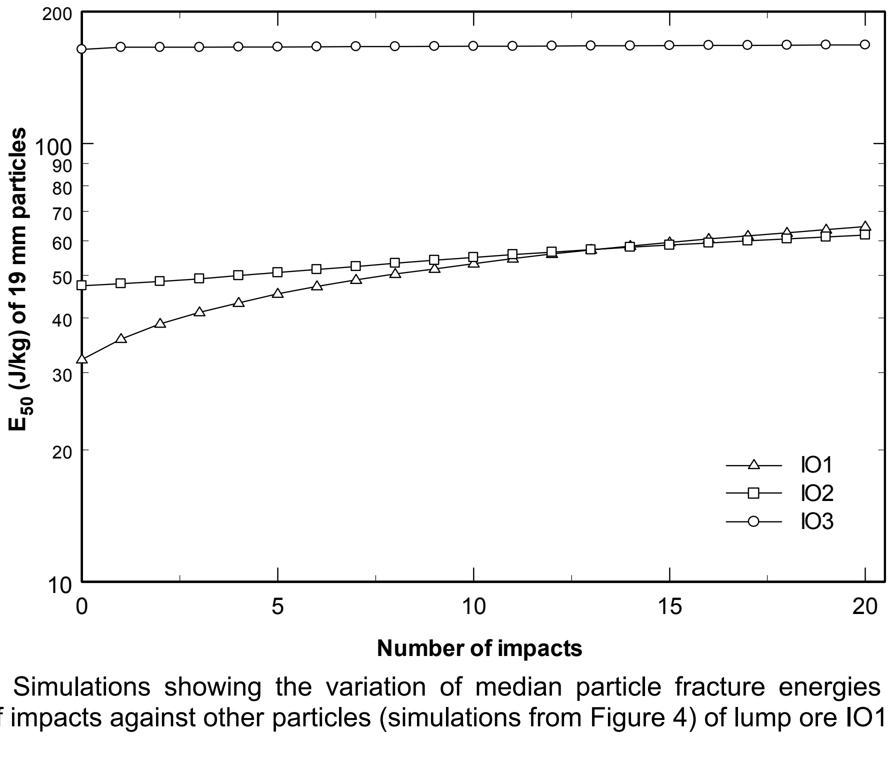

Figure 6. Simulations showing the variation of median particle fracture energies as a function of number of impacts against other particles (simulations from Figure 4) of lump ore IO1

Finally, the contribution of surface abrasion (called “handling” by some researchers[6]) that is predicted in the present model from testing using a 30-cm mill (0.01 to 0.025%/impact – Table 2) was significantly smaller than estimates by Weedon and Wilson[6] for an Australian lump ore (Mt. Newman), equal to

0.6%/impact. This and other evidences suggest that a more detailed description of this phenomenon may be necessary for its precise simulation.

5 CONCLUSIONS

A fundamental model of degradation of ores as a result of drops and transfers has been developed and validated using data from repeated drops of a Brazilian iron ore against a steel plate in the laboratory.

The model was then used to simulate the influence of ore type, impact height, number of drops and impact surface on the proportion of fines (-6.4 mm material) using data from iron ores from Brazil and North America. The model also predicted the phenomenon of stabilization, by which particles that are not broken become progressively tougher as a result of repeated impacts. Finally, the model was also able to demonstrate that by changing the order of drops of different magnitude, the proportion of fines changes, with the greatest degradation occurring from impacts at high magnitude earlier in the handling process rather than later.

This model, which can be used to predict the response to handling of different ore types within a deposit, requires fitting a number of material-specific parameters. However, these parameters can be fitted from controlled testing on single particles in the impact load cell, a drop weight tester. Further, these same parameters are not system-specific, so that they can be used not only to simulate degradation due to handling, but also comminution in crushers and mills using state-of-the-art fundamental models under development in the authors' laboratory.

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