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Method for quick assessment of cohesive ore flowability

Método de quantificação expedita da escoabilidade de minério coesivo

Método de cuantificación expedita de la fluidez de mena cohesiva

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Abstract

Beneficiation of iron ore with natural moisture has become increasingly relevant, either due to restrictions on wet operations, which result in disposal of tailings in dams, or due to the possibility of ready blending of various ore types. A great difficulty in these operations is handling of hydrated ores, with the presence of clay minerals, or with a higher moisture content. Effective techniques to facilitate handling emerge as the main challenge to make it possible to treat these ores under natural moisture in different plants around the world. This work aims at presenting a method for expeditious appraisal of the flowability of cohesive ore. A sample of iron ore from Mina do Pico, Brazil, was used in this study. The flowability was investigated under different conditions, using a bench scale rectangular trough with controlled slope. The following liners were studied: ASTM A-36 carbon (CDP), ultra-high molecular weight polyethylene (UHMW), Hardox, natural rubber, Arcoplate and polyurethane. UHMW resulted in the best flow efficiency and the lowest friction angle between bulk ore and the lined wall. Vibration as an ancillary agent for mechanical discharge significantly improved the flow efficiency.

Keywords: Bulk solid handling; Natural moisture; Cohesive ore; Coating; Rheology.

Resumo

O beneficiamento do minério de ferro sob umidade natural tem se tornado cada vez mais relevante, seja pelas restrições às operações a úmido, que resultam na disposição de rejeitos em barragens, seja pela possibilidade de pronta mescla de diversos tipos de minério. Uma grande dificuldade nestas operações é o manuseio de minérios hidratados, com presença de minerais argilosos, ou com maior umidade. Técnicas eficazes para facilitar o manuseio surgem como o principal desafio para viabilizar o tratamento desses minérios sob umidade natural em diferentes usinas ao redor do mundo. Este trabalho tem como objetivo apresentar um método para avaliação expedita da escoabilidade de minério coesivo. Uma amostra de minério de ferro da Mina do Pico, Brasil, foi utilizada neste estudo. A escoabilidade foi investigada sob diferentes condições, empregando uma calha retangular, em escala de bancada, com declividade controlada. Foram estudados os seguintes revestimentos: carbono ASTM A-36 (CDP), polietileno de ultra-alta massa molecular (UHMW), Hardox, borracha natural, Arcoplate e poliuretano. O UHMW resultou melhor eficiência de escoamento e menor ângulo de atrito estático entre o minério a granel e a parede revestida. A vibração como agente auxiliar para descarga mecânica melhorou significativamente a eficiência do escoamento.

Palavras-chave: Manuseio de granéis; Umidade natural; Minério coesivo; Revestimento; Reologia.

Resumen

El beneficio de menas de hierro con humedad natural se ha vuelto cada vez más relevante, ya sea debido a las restricciones en las operaciones húmedas, que resultan en la eliminación de relaves en presas, o debido a la posibilidad de mezcla lista para varios tipos de menas. Una gran dificultad en estas operaciones es el manejo de menas hidratadas, con presencia de minerales arcillosos, o con mayor contenido de humedad. Técnicas efectivas para facilitar el manipuleo emergen como el principal desafío para hacer posible el tratamiento de estas menas bajo humedad natural en diferentes plantas alrededor del mundo. Este trabajo tiene como objetivo presentar un método para la evaluación expedita de la fluidez de menas cohesivas. En este estudio se utilizó una muestra de mena de hierro de Mina do Pico, Brasil. La fluidez se investigó en diferentes condiciones, empleando un canalón (artesa) rectangular a escala de banco de pendiente controlada. Se estudiaron los siguientes revestimientos: carbono ASTM A-36 (CDP), polietileno de ultra alta masa molecular (UHMW), Hardox, caucho natural, Arcoplate y poliuretano. UHMW dio como resultado la mejor eficiencia de flujo y el ángulo de fricción más bajo entre el sólido a granel y la pared revestida. La vibración como agente auxiliar para la descarga mecánica mejoró significativamente la eficiencia del flujo.

Palabras clave: Manejo de sólidos a granel; Humedad natural; Mineral cohesivo; Revestimiento; Reología.

1. Introduction

Beneficiation of iron ore with natural moisture has become increasingly relevant, for its possibility of ready blending of various ore types and for it does not require waste disposition in dams, as in wet operations. Handling of weathered materials is a great concern, especially for those goethitic and for those containing clay minerals, in the presence of higher moisture content, which tend to be cohesive, requiring additional care for hauling, conveyance, transfer and even their processing. In such cases, flow interruptions in the beneficiation and loading circuits are prone to occur. In addition to the impact on the production system (which can last for several hours), especially in the rainy season, the operators' risk exposure in clearing activities is quite high.

Bulk solid handling has been poorly studied when compared to fluid handling (Woodcock & Mason, 1995). The first systematic work in this area is attributed to Roberts in 1884 (Schulze, 2008). Roberts performed tests on physical models and established that the pressures on the walls did not increase linearly with the depth, but that a fraction of the weight of the stored product was transferred to the walls by friction. The most important research in the area of handling bulk solids was developed by Dr. Andrew W. Jenike, when in the 1950, he looked for a field in which he could make a unique and significant engineering contribution. Jenike set up the "Bulk Solid Flow Laboratory" at the University of Utah (Schulze, 2008). The results of this extensive work were published in the early 1960 (Jenike, 1964; Jenike, 1989) and are still a reference today.

In an attempt to characterize the flowability of the various bulk materials handled, several methods have been proposed, with different degrees of complexity of execution and reproducibility, among which we can mention, for example, the dynamic angle of repose, the angle of internal friction, the Hausner ratio and the Jenike cell shear test (like that one discussed by Bandeira et al., 2021, and Dornelas et al., 2021).

The determination of the flow properties relevant to the characterization of bulk materials is usually carried out by shear testing, which is a time-intensive and expensive procedure. Within the context of simplification, the correlation between the flow properties measured by the shear cell and the Hausner ratio has proved to be good (resulting in small errors) for materials categorized as cohesive and very cohesive (Saw et al., 2015).

Under this approach the present work proposes a quick method for appraisal of flowability of cohesive ore on different liner surfaces.

2. Material and Methods

2.1 Ore sample

A sample of iron ore, from the iron ore Pico Mine (latitude 20° 12' 53" South, and longitude 43° 51' 22" West), in the mineral province named Iron Quadrangle, Brazil, was collected at ITM-I processing plant. Pico Mine is an operational unit of Vale S/A company, located in the municipality of Itabirito. It is currently part of the Vargem Grande mining complex.

2.2 Sampling and preparation

Sampling procedure was performed using a cross belt automatic sampler (from Engendrar, model AMM-1000), installed on the belt conveyor at ITM-I. The increments had been taking place systematically, over a period of one week. The mass of each increment was about 5.4 kg. Approximately 150 kg of ore were collected at regular intervals of 6 h, which were accumulated, homogenized, quartered, and separated into smaller portions for laboratory tests.

2.3 Samples of industrial liners

The different surfaces for the experiments were obtained from samples of industrial lining materials usually applied in the various ore beneficiation plants in Brazil. They are listed in sequence.

Arcoplate: It is a wear-resistant fused alloy steel plate with a chromium carbide rich overlay plate. Main applications are soil penetration blades, transfer chutes, vibrating grills, and pipes (Martin Engineering, 2019); supplier: Martin Engineering.

Hardox: Hardox is a wear-resistant steel with controlled addition of carbon, silicon, manganese, chromium, nickel, molybdenum and boron (Oliveira et al., 2017; Białobrzeska, 2021). Main applications: truck and excavator buckets, soil penetration blades, transfer chutes, vibrating grills, and crusher liners; supplier: SSAB. (Ssab, n. d.).

CDP — CastoDur Diamond Plate: ASTM A-36 carbon steel with welded coating. Main applications: truck and excavator buckets, soil penetration blades, transfer chutes, screens, pipes and crusher plates; supplier: Eutectic Castolin (Silva, 2016; Eutectic Castolin, 2017; Březina et al., 2004).

Duramaxx: Ultra high molecular weight [sic] polyethylene (UHMW Duramaxx). Main applications: technical parts, molded plates, nonstick liners for truck buckets, bulldozer blades, bins, and transfer chutes (Brasken, 2020); supplier: Baron Nonstick Coatings.

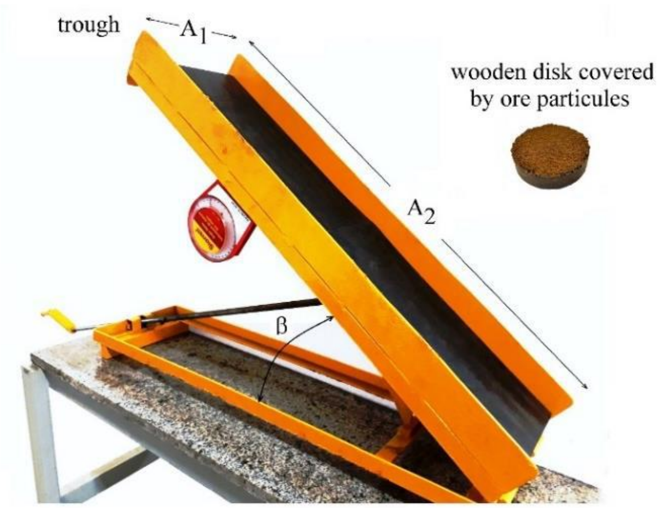
Polyurethane: Main applications: technical parts, gaskets, sieve screens, sealing rings, joints for rails, hydrocyclone components and pipe linings (Mano, 1991); supplier: Haver & Boecker.

Natural rubber: Manufacture of tires, screens decks, hoses, shock absorbers (cushions), technical parts and tank linings, liner for slurry pump casings and pipes; supplier: Haver & Boecker.

2.4 Controlled slope chute

The initial objective was to simulate the flow through a physical model (Figure 1), based on Rastogi et al. (1993) and Silva (2005), in order to obtain parameters for assessing the flowability of the bulk material under a certain slope condition, characteristic of the wall surface and moisture content. The chute or trough simulates the behavior of the gravity flow of bulk solids in a straight chute (Figure 1). This apparatus has a controlled tilting trough, with dimension 200 mm x 800 mm, in order to evaluate the flowability for industrial linings commonly found on the market size (195 mm x 395 mm). A hand-operated screw rod was used to adjust the slope accurately. An inclinometer (equipped with a magnetic base) was installed to the lower part of the chute. The trough was made in 1045 carbon steel, with a robust structure to support the load of two plates of metallic liners, whose total weight can reach approximately 22 kg.

Figure 1. Trough for flow tests and disk with ore particles glued on its base. $\boldsymbol{A_1}$ = 0.200 m; $\boldsymbol{A_2}$ = 0.800 m.



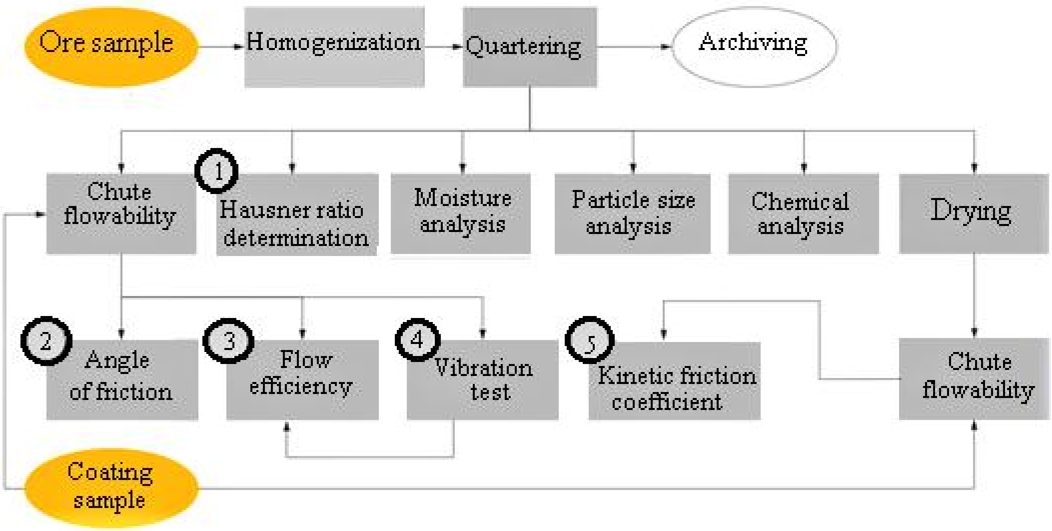
Source: Authors' own elaboration.

2.5 The flowability assessment

The procedure has combined five parameters, namely: *Hausner ratio (HR*, the ratio between compacted and loose bulk densities), which characterizes the flowability of the bulk material (Saw et al., 2015; Riley & Mann,1972; Milhomem & da Luz, 2016; Hao, 2015); *angle of wall friction*, which determines the smallest angle that triggers the gravity flow of bulk material (Silva, 2005; Clayton, 2019); *flow efficiency*, which indicates the percentage of bulk material that flows along the lined channel, in order to assess the moisture impact; *vibration test*, which aims to evaluate the increase in flow efficiency, when the surface is subjected to vibration (Woodcock & Mason, 1995; Schulze, 2008) and *kinetic friction coefficient* (μ_k), which infers the flow resistance due to the surface roughness.

Complementarily, moisture analysis (by conventional aquametric method), determination of particle size distribution using wet sieving, and chemical analysis by X-ray fluorescence (using molten KBr tablets), were carried out to support this study. Figure 2 illustrates the methodological route.

Figure 2. Methodology for assessing the flowability of cohesive ores.



Source: Authors' own elaboration.

Determination of the Hausner ratio (HR)

The Hausner ratio (*HR*) was chosen as the main parameter for evaluating the flowability of the material under research, under different moisture ranges. For its determination, a 500 ml beaker and an analytical balance with a minimum precision of two decimal places were used. The usual tapping method was followed. The ***HR*** was obtained by constructing number of mechanical taps versus ***HR*** curves, and the value considered was obtained after the final asymptotical compaction of the sample in the beaker. The compaction was done manually, by drops of the beaker on a rubber surface, at an impact height of approximately 25 mm. Basically, the procedure adopted here was the one recommended by Milhomem and da Luz (2006).

Angle of wall friction

The determination consisted of feeding approximately 0.5 kg of material in the chute, gradually increasing the slope to the point where the total flow of the sample occurred, recording the ultimate (final) angle (β).

Flow efficiency

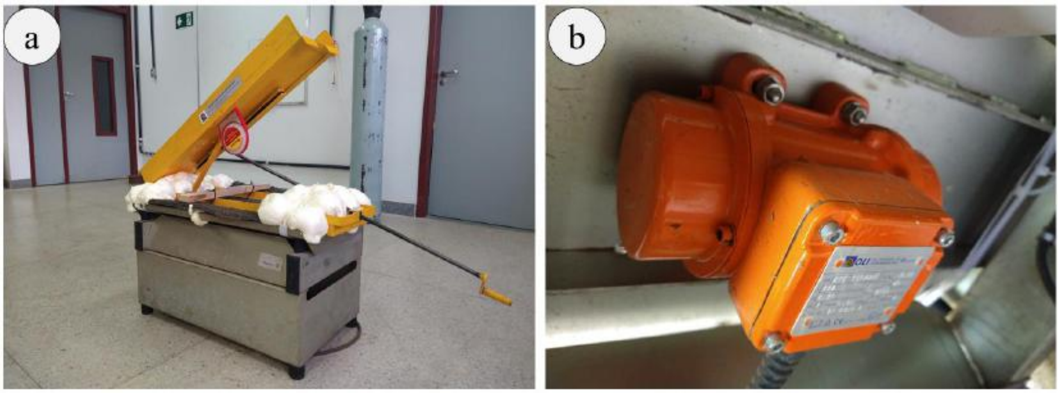
Normally, iron ores under natural moisture flow at angles greater than 40°. The purpose of this evaluation is to compare the efficiency for different surfaces, using a simple and easy to understand parameter, in an intermediate flowability domain. The determination was made with the trough adjusted to the angle (***β***) of 30°. After feeding the trough with sample of approximately 0.5 kg, the material was allowed to slip on the bottom of the trough. The amount that flowed and the amount that remained on the channel surface was then weighed. The efficiency (equation 1) is the ratio of flowing mass (drained) to fed mass (drained + retained).

$$Efficiency = \frac{Drained\ mass}{Drained\ mass + Retained\ mass} \qquad (1)$$

Vibration test

To assess the effect of vibration as a mechanical discharge aid, the tough was installed on a concrete densification vibrating table, model Viatest B3–7 (Figure 3.a). The table has an OLI motor-vibrator with a frequency of 60 Hz and a centrifugal force ($\boldsymbol{F_c}$) of 1.18 kN (Figure 3.b). The flow efficiency was evaluated by varying the vibration time, and the mass drained in each interval, for different moisture contents and surface types.

Figure 3. Apparatus for testing with vibration: a) chute installed on a vibrating table; b) motor vibrator under the table.



Source: Authors' own elaboration.

Determination of the kinetic friction coefficient

The coefficient of kinetic friction ($\boldsymbol{\mu_k}$) between the dry bulk material and the surface, infers resistance to movement caused by roughness and/or type of coating during gravity flow in a transfer chute. The procedure consisted of feeding approximately 0.5 kg of dry material in the chute and gradually increasing the slope until the total flow of the sample. Then, the tangent of the final angle (***β***) was calculated, according to the inclined plane method, where $\boldsymbol{\mu_k}$ = tan (***β***). Dry bulk material sample sieved below 2.0 mm was used, as standard size range, in this work.

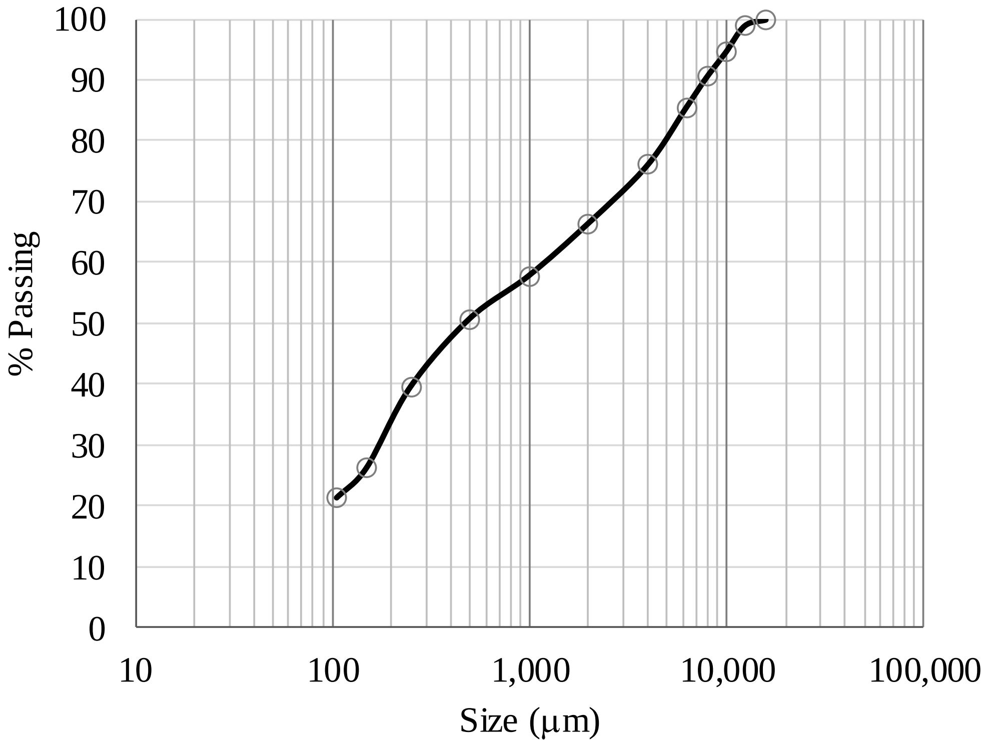
To determine the $\boldsymbol{\mu_k}$ of the mineral particles on the coatings, without considering the effect of particle rolling or induced movement caused by the shock between the particles, a wooden disk of 90 mm in diameter and 15 mm in thickness was used. One layer of dry ore particles in the size class 2.0 to 0.5 mm was glued on the disk's bottom face. The particle size range chosen corresponds to the central region of the amplitude (Figure 1). The disk was positioned on the liner's plates at the channel bottom, with the "ore face" down. Gradually the slope was increased until the disk slid in a continuous way. The ultimate angle (***β***) for loose bulk material was calculated in the same way.

3. Results and Discussion

3.1 Particle size distribution

Mineral sample under study has 80 % passing through 5.0 mm and average diameter measuring (***d_{50}***) equal to 0.5 mm. The particle size analysis is shown in Figure 4.

Figure 4. Particle size distribution of the product of ITM-I processing plant at Mina do Pico.



Source: Authors' own elaboration.

3.2 Chemical composition

The chemical composition of the sample is shown in Table 1 (in that table ***LOI*** stands for loss on ignition, which is the total volatile content in sample).

Table 1. Chemical analysis by particle size range.

Size range [mm]	**Distribution [%]**	**Fe [%]**	**SiO_2 [%]**	**Al_2O_3 [%]**	**P [%]**	**Mn [%]**	**LOI [%]**
Global	100.0	58.35	8.75	2.24	0.081	0.096	5.47
From 19 to 6.3	14.5	60.96	3.64	2.65	0.084	0.077	6.37
From 6.3 to 2.0	19.1	61.52	2.75	2.56	0.090	0.114	6.64
From 2.0 to 0.5	15.7	59.84	4.12	2.77	0.102	0.129	6.70
From 0.5 to 0.15	24.6	53.3	17.15	1.95	0.075	0.095	4.88
From 0 to 0.15	26.1	58.44	10.84	1.72	0.066	0.076	3.93

Source: Authors' own elaboration.

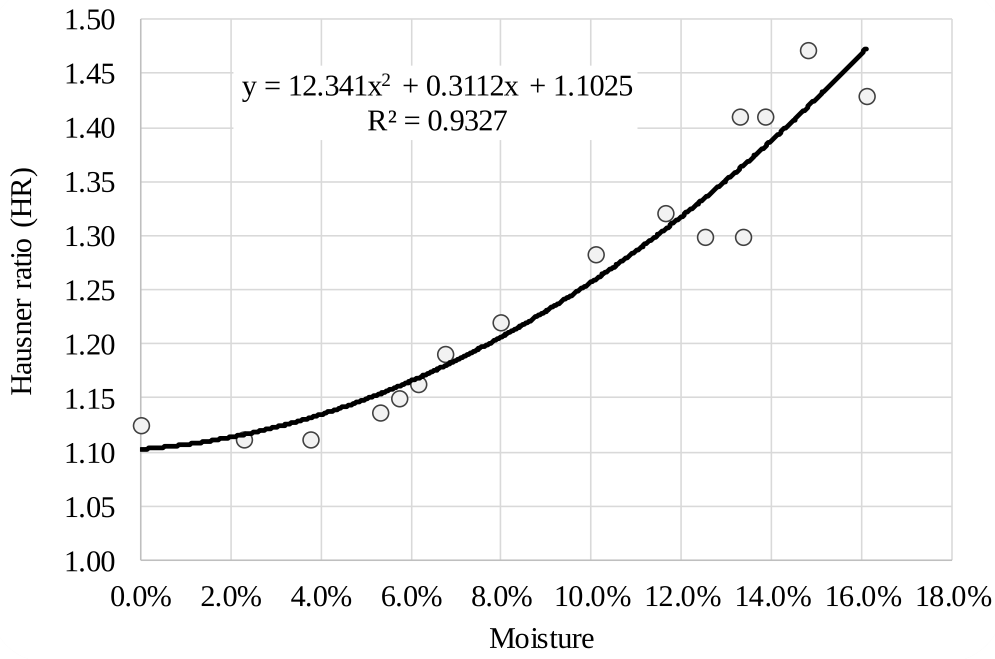
3.3 Hausner ratio (*HR*)

The number of beats (by tapping) to stabilize the compacted (tapped) specific mass (ρ_c) occurred after 200 beats. The influence of moisture on ***HR*** at different levels was also evaluated (Figure 5). It can be seen that ***HR*** exceeds 1.25 with 10.0 % moisture, and, therefore, the ore can be classified as cohesive, being necessary use of lubricants or special liners in order to get flow occurrence without interruptions (Milhomem & da Luz, 2016). The correlation between the ***HR*** and the moisture content was quite high, with a Pearson's coefficient of determination (R^2) equal to 0.9327. The resulting equation is:

$$\boldsymbol{HR} = 12.34\boldsymbol{u}^2 + 0.3112\boldsymbol{u} + 1.1025 \qquad (2)$$

Where $\boldsymbol{u}$, in the precedent equation, is the moisture content (in fraction) in the bulk material. Naturally, the previous equation is valid only in the tested experimental boundaries, even because, after a critical value of humidity, the liquefaction of the system occurs, drastically changing its rheological properties.

Figure 5. Hausner ratio ($HR = \rho_c/\rho_0$) at different moisture contents.



Source: Authors' own elaboration.

3.4 Angle of wall friction

Flow tests were performed using the collective sample, below 19 mm. The results for the angle of friction against the wall are shown in Table 2. The sample had a moisture content adjusted to 13.8 % and an ***HR*** = 1.41.

Table 2. Angle of wall friction for the different coatings tested.

Coating	Friction angle [°]
CDP	45.5
UHMW	40.0
Hardox	41.8
Natural	49.0
Arcoplate	47.8
Polyurethan	43.8

Source: Authors' own elaboration.

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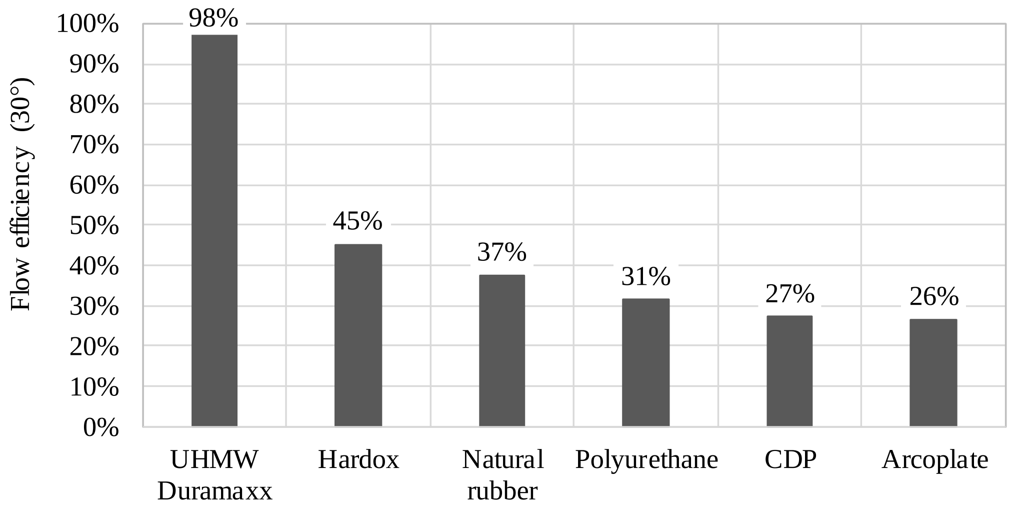
3.5 Flow efficiency determination

The bulk material flowability, or flow efficiency determination was carried out in accordance with the procedure previously described. The data presented in Figure 6 also refer to the sample of cohesive ore, with a moisture content adjusted to 13.8 % and an ***HR*** equal to 1.41.

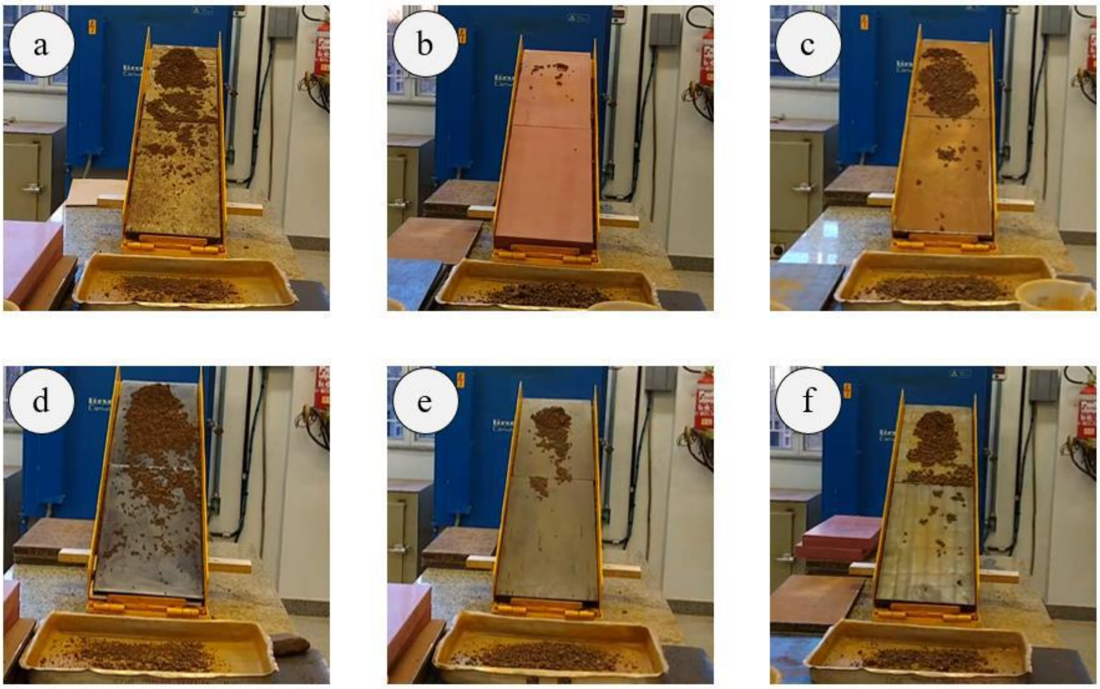
Figure 6. Flow efficiency at an angle of 30° for the different coatings.



Source: Authors' own elaboration.

Tests to determine the efficiency of fluidity at slope of 30 ° have made it possible to quickly compare which material is most appropriate for a given application. The images shown in Figure 7 illustrate these differences.

Figure 7. Aspects of flow efficiency tests: *a*. Arcoplate; *b*. UHMW Duramaxx; *c*. Hardox; *d*. Polyurethane; *e*. Natural rubber; *f*. CDP.



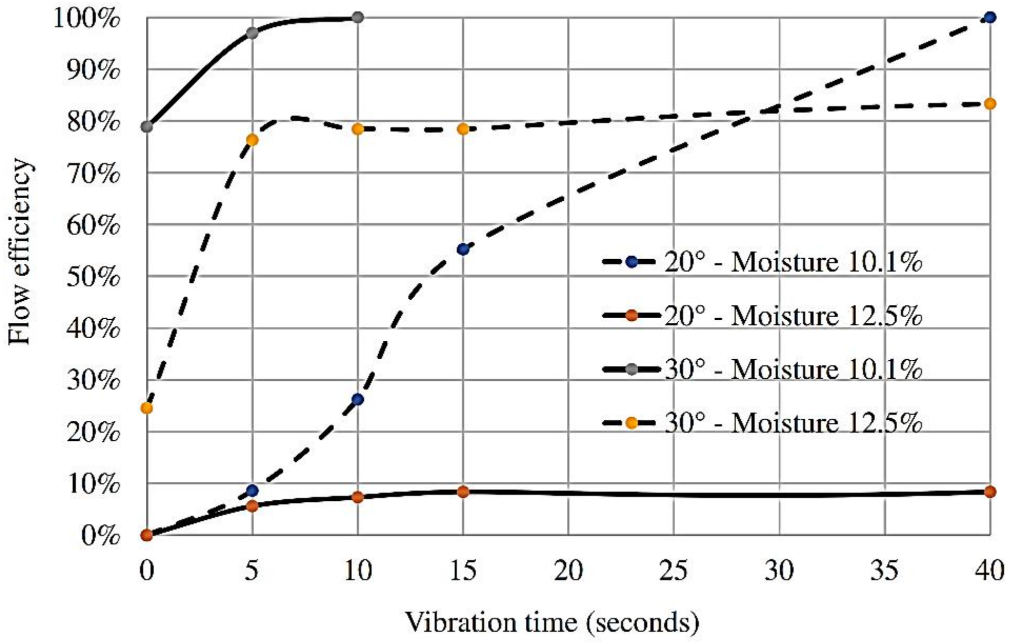
Source: Authors' own elaboration.

It can be clearly seen that the best flowability occurred on the ultra-high molecular weight polyethylene (Duramaxx) surface (photo ***b***, in Figure 7), since it was the alternative that retained less material on the inclined surface of the channel.

3.6 Vibration tests

In order to investigate the effect of vibration on the flow efficiency, experiments using the rubber liner was firstly evaluated, once this material normally presents a lower performance than the others ones here evaluated, under static conditions. The slopes of 20° and 30°, and moisture levels of 10.1% and 12.5% were selected for evaluation. Figure 7 shows that, despite the increase in flow efficiency from the vibration start, moisture and friction angle continue having strong influence on the results.

Figure 7. Flow efficiency with the use of vibration in rubber lining.



Source: Authors' own elaboration.

The effect of mechanical vibration on the flow efficiency at a slope angle of 30° was verified comparatively for the different surfaces under study, using a sample of cohesive ore with moisture adjusted to 11.3 %. Table 3 shows that all coatings, even the with the worst flow performance, they managed to reach efficiency above 95 % with just 5 seconds of vibration, however the metallic coatings presented greater difficulty in draining 100 % of the mass, even with relatively high vibration time (75 seconds).

Table 3. Flow efficiency with vibration in the different coatings.

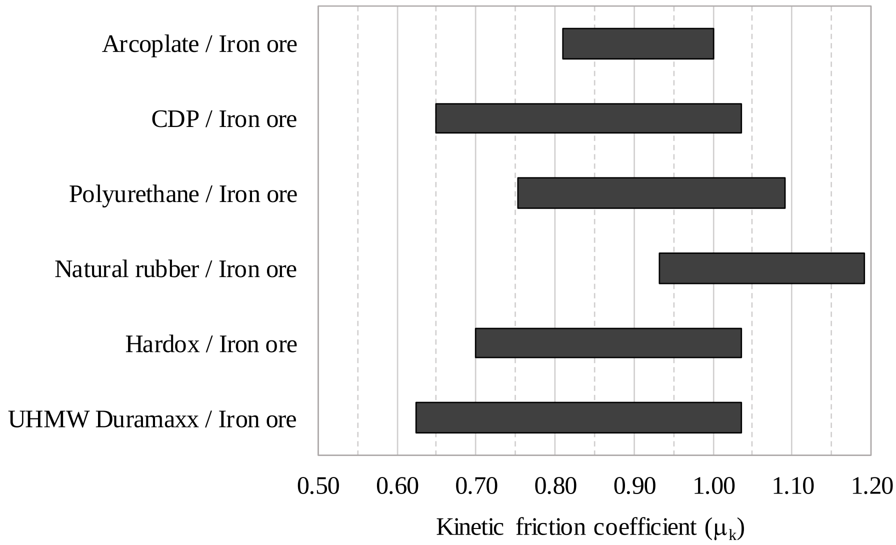
Liner material	Vibration time (seconds)	
	0.0	75.0
CDP	32.3 %	99.6 %
UHMW	70.8 %	–
Hardox	38.1 %	99.9 %
Natural rubber	46.3 %	–
Arcoplate	33.4 %	99.9 %
Polyurethane	48.0 %	–

Source: Authors' own elaboration.

3.6 Kinetic friction coefficient

The coefficient of kinetic friction (μ_k) between the different surfaces and the dry bulk ore was determined according to the method described in item 2.5. The sliding of the ore-impregnated wooden disk was considered to determine the minimum value of each range presented in Figure 9, while the corresponding maximum value was obtained considering the flow of the "loose" material below 2.0 mm.

Figure 8. Kinetic friction coefficient (μ_k) between the iron ore and the different surfaces evaluated.



Source: Authors' own elaboration.

4. Conclusion

The present work has showed it is possible to combine the use of physical models and experiments of low cost and low complexity, such as he Hausner ratio determination, to evaluate the flowability of cohesive ores on different surfaces. This research has demonstrated it is possible use the procedure here presented as a preliminary tool for fast characterization of cohesive bulk solids flowability, which can be used by students and professionals dealing with handling operations of cohesive bulk materials, especially to identify which liner is most suitable for a given application.

The Hausner ratio can be further explored in mineral engineering, especially due its ease of execution and the possibility of obtaining correlations, which go beyond the characterization of the fluidity of bulk materials.

The tests to determine the angle of wall friction, and also the flow efficiency directly provide the expected behavior for a given liner, allowing one to select the most suitable material for the application. It is important to highlight the hardness or abrasion resistance of the materials was not considered here. Therefore, for heavy duty application, with direct impact and handling of very abrasive ores, it is recommended to opt for metal liners of greater hardness. In this instance Hardox proved to be one of the promising options.

For those applications whose main difficulty is flowability, ultra-high molecular mass polyethylene has proved to be the best choice, with a significant difference in flow efficiency, compared to the other liners tested.

Vibration as an auxiliary agent for mechanical discharge significantly improved the flow efficiency, alleviating flow problems, without requiring major investments, especially in changes of the installation's layout.

When it comes to the kinetic friction coefficient (***μk***) between the different surfaces and the ore under evaluation, it should not be the only parameter to characterize the liner efficiency from the point of view of flowability. But, at least, it does allow inference about the influence of type and surface finishing on the handling operation. In this sense, again ultra-high molecular mass polyethylene appears as a coating of less $\boldsymbol{\mu_k}$, but with a range amplitude that covers other materials. This overlapping of $\boldsymbol{\mu_k}$ ranges, for dry ore, and the large differences in flow efficiency for wet ore, suggest that the liners have different degrees of hydrophilicity and that this parameter affects the bulk material flowability on them. Further research is recommended in this regard.

As a final remark, it is interesting, in the future, to expand the scope of the present investigation, carrying out an extensive experimental campaign, in terms of rheological and tribological parameters for the studied ore. This effort can enable the establishment of multivariate statistical correlations, allowing the implementation of mathematical models, in order to predict its behavior in face of the antiabrasive coating of channels and chutes for handling the bulk solids under study. Undoubtedly, these is a promising topic for the continuity of this research, which will result in useful future publications.

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