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# Optimization of screen dewatering through dynamic control of frequency

## Otimização de desaguamento por peneira via controle dinâmico da frequência

## Optimización del desagüe por criba a través del control dinámico de la frecuencia

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**Abstract**

This paper is intended to explore how changing the frequency of industrial screens processing the dewatering of an iron ore bulk influences the final moisture content. Screen dewatering of particulate systems in size range between 150 μm and 1000 μm, from iron ore, was studied in an industrial environment. The oscillating dewatering screen employed has effective dimensions of 4.2 m long by 1.8 m wide. The screen frequency was controlled by a frequency inverter in the electric circuit of the motor drive. A reduction in the final cake moisture was observed by reducing the frequency. Furthermore, differences between the intrinsic oscillation parameters of the bulk material and that of the oscillatory electromechanical system were detected. To achieve this controlled variation of the frequency levels followed, initially, a continuous level regime (30 minutes per condition), and, later, a sinusoidal and a stepped (squared form at 30 seconds per level) regime. The adoption of the sinusoidal and stepped regime allowed the matching of the same vibrational parameters of the particulate bed with those of the screen, leading to a reduction in the moisture content in the final cake.

**Keywords:** Moisture; Iron; Ore; Mineral; Processing; Screening; Particle; Classification.

**Resumo**

Neste trabalho pretende-se explorar como a alteração da frequência de peneiras industriais processando o desaguamento de um granel de minério de ferro influencia na umidade final. Desaguamento por peneiramento de granéis bitolados entre 150 μm e 1000 μm e oriundos de minério de ferro foi estudado em usina industrial. A peneira desaguadora oscilatória empregada tem dimensões efetivas de 4,2 m de comprimento por 1,8 m de largura. A frequência da peneira era controlada por inversor de frequência no circuito elétrico de acionamento do motor. Observou-se a redução da umidade da torta final com a alteração da frequência. Ademais, diferenças entre os parâmetros de oscilação intrínseca do leito de granéis e a do sistema eletromecânico oscilatório foram detectadas. A variação controlada dos níveis de frequência seguiu, inicialmente, regime de patamares contínuos (30 minutos por condição), e, posteriormente, regime senoidal e regime de função tipo degrau (30 segundos por condição). A adoção do regime senoidal e em degrau permitiu o sincronismo dos parâmetros oscilatórios do leito de granéis levando à redução da umidade final da torta.

**Palavras-chave:** Umidade; Minério; Ferro; Processamento; Mineral; Classificação; Partículas.

**Resumen**

El objetivo de este trabajo es explorar cómo influye el cambio de la frecuencia de las cribas industriales que procesan el desagüe de un granel de mineral de hierro en el contenido final de humedad. El desagüe por criba de sistemas de partículas en rango entre 150 μm y 1000 μm, provenientes de mena de hierro, se estudió en un entorno industrial. La criba desaguadora oscilante empleada tiene unas dimensiones efectivas de 4,2 m de largo por 1,8 m de ancho. La frecuencia de la criba fue controlada por un inversor de frecuencia en el circuito eléctrico del accionamiento del motor. Se observó una reducción en la humedad de la torta final al reducir la frecuencia. Además, se detectaron diferencias entre los parámetros de oscilación intrínseca del lecho a granel y el del sistema electromecánico oscilatorio. Para lograr esta variación controlada de los niveles de frecuencia se siguió, inicialmente, un régimen de mesetas continuas (30 minutos por condición), y, posteriormente, un régimen sinusoidal y escalonado (forma cuadrática a 30 segundos por nivel). La adopción del régimen sinusoidal y escalonado permitió igualar los mismos parámetros vibratorios del lecho de partículas con los de la malla, lo que llevó a una reducción del contenido de humedad en la torta final.

**Palabras clave:** Humedad; Mena; Hierro; Procesamiento; Minerales; Tamizado; Clasificación; Partículas.

## 1. Introduction

The Brazilian mineral production industry, especially the iron ore industry, has been continuously adopting changes in processes to meet the needs of the commodities market. Additionally, nowadays, after the huge accidents related to dam breaks in 2015 and 2019, this industry is facing challenges that demand new technologies, new processes, and procedures to reach productivity, safety, quality, and social requirements.

Among these challenges, two have been of great importance, associated with the productivity: the classification of ore (run of mine) with high iron content, generating products sizes below 19 mm, and the solid-liquid separation of sinter feed products. The common point of these challenges associated with mineral processing is that oscillatory equipment (screens) can be used in both processes.

Iron ore products from a high-grade run of mine are a way to decrease the need for tailings dams, since this type of ore only requires particle sizes control to make it profitable, and does not depend on the mineral concentration, which produces tailings. However, friable ores with a higher percentage of laterites interact with moisture and make particle size control a challenge. Fang et al. (2019) and Gonçalves e da Luz (2022) have studied the effect of high tensile of wet and sticky iron ore to understand handling problems, one of their understood was that the increase of fines in the ore can be able to power up adhesive characteristics.

According to Chaves and Peres (apud Iizuka, 2006) the classification of a population of particles in two different size fractions is performed with the presentation of all these particles to the classifier surface (screen deck). Thus, it is necessary that the particles must be free from bulk so that they have a chance to be compared with the openings of the classifying surface. Sousa et al. (2020) mentioned that screening and modern ore sorting are the large methods of pre-concentration. Other technologies have been developed to classify ore by size, in their work Liu et al. (2021) tried to apply artificial intelligence in ore image to sort particles by size.

Thus, classification screening is a mechanical process in which a particulate stream flows on surface provided with openings, and particles larger than the openings overwhelmingly do not pass through them, while, on the other hand, particles smaller than the openings tend to pass through, according to monotonically decreasing probabilities with their size. For screening of high-grade iron ore there is a need to adapt this process to the mineralogical and quality variations, since the presence of friable and fine ores leads to reduced screening efficiency, as commented by de São José et al. (2017). Another example came from Srikakulapu et al. (2021), in which was mentioned the difficulty of handling the iron ore with fines before feeding the LD process. As the definition fines, in the works of the area, it refers to the population of particles that are much smaller than the openings of the screen used for separation.

Interaction between very fine particles and water is usually harmful for particle size control, because moisture, below the fluidization point of the granular system, agglomerates, almost completely, the particles into clods, causing sizing equipment to lose performance; as mentioned by Plinke et al. (2016) ore with high adhesive characteristics are usually known as wet and sticky ores.

It should be noted, for completeness of the comment, that even in particular none densified systems (such as slurries), this interaction of water with fines may also cause aggregation induced by complex electrochemical and interface phenomena (homo- or heteroaggregation).

Was found by Marín-Rivera et al. (2017) that the wettability (interaction between water and iron ore) is more dependent on iron ore origin (geological location of the mine) than the ore composition (mineralogical composition).

This loss of ability to access the particles reduces the probability of size separation by the screen apertures. In other words, this effect reduces screening efficiency, since particles much smaller than the classification apertures are retained as they are trapped in the bed by agglomeration forces caused by the moisture content in the ore. This difficulty in sizing generates wasteful reprocessing, raising the operation cost. In line with this concern, Jiang et al. (2017) reported that the efficient screening can saves coal preparation cost, optimizes product structure and generates economic benefits, and, in addition, also improves energy efficiency and reduces carbon dioxide emissions. Actually, many ways have been developed to better understand of screen efficiency, for example, to reach a model for banana screen Jahani et al. (2015) extensively used discrete element method (DEM) to directly simulate the screening process.

The second challenge for the minerals industry is related to solid-liquid separation. Here the processing of sinter feed products can result in high moisture bulks. As far as solid-liquid separation is concerned, slurries are usually fed into filters (vacuum filters, in most cases), which — as is to be expected — have better performance (in terms of productivity and final cake moisture) with a higher percentage of solids in the feed, as pointed out by Herath et al. (1992). In line with this, dewatering screens are sometimes used before filter installations to provide sufficiently concentrated filter feed.

High moisture can affect shipping transportation. Ferreira (2019) mentions that the maritime transportation of ores is an essential process in the productive chain of mining, and is regulated at the international by the International Maritime Organization (IMO), the regulatory body for the safety of maritime transport operations.

This organization established the IMSBC, which is the maritime code for dry bulk commodities. This code establishes strict parameters for the transport of bulk materials. The objective of establishing these parameters is to avoid accidents with vessels due to circumstances linked to the nature of the bulk materials that cause loss of stability (in particular due to the evolution of the vertical moisture gradient of the cargo), structural damage, and damage due to chemical attacks on confinement walls.

Some types of iron ore products, such as pellet feed and coarse sinter feed, are classified as bulk materials that are susceptible to liquefaction in ship holds. This characteristic causes the ore to move in the ship's holds, changing the center of mass and causing the ship to list and ultimately, the ship to lose stability. Mohajeri et al. (2020) have introduced an interesting flowchart of controllable and uncontrollable variables in bulk storage and transport processes which try to create a model for design.

In his work Ferreira (2019) determines that the phenomenon of liquefaction in bulk materials occurs according to a certain force field on a system of fine particles and moisture if the moisture is above the transportable moisture limit (TML). In order to reduce this hazardous behavior, it becomes necessary to control the moisture of the bulk ores mentioned. This control must monitor the moisture, so as not to allow exceeding the safety limits.

Flowability of densified granular systems, under a gravitational field, depends on the morphometric aspects of the particles, the interstitial porosity and their degree of saturation. This degree of saturation can evolve generating vertical moisture gradients during storage. If the granular system can be described by a Rosin–Rammler–Sperling–Bennett distribution with sharpness index, $\boldsymbol{n}$ (and a generical median size $\boldsymbol{x_{50}}$), Prado et al. (2022) showed the bed porosity after random packing of the bulk material, provided the particle are spheroidal in shape, is given for the following equation:

$$\varepsilon(n) = 0.2204 \times \left[1 - e^{-\left(\frac{n}{1.1419}\right)^{1.4411}}\right] + \ 0.1503 \tag{1}$$

In turn, Nabawy (2014), advocated the following equation for porosity of sandstones as a function of the elongation ($\boldsymbol{E}$ — the length to diameter ratio) of particles:

$$\varepsilon(E) = \frac{0.26188}{E} + 0.21431 \tag{2}$$

In addition to pore pressure, friction between the granules that make up a bulk material also plays a major role in liquefaction phenomena. Obviously, the interparticle friction will be a monotonically increasing function of the number of contact points, namely the average coordination number of the particles. Treating empirical data from Wakeman & Tarleton (2005), the present authors obtained, by nonlinear regression, the following relationship between the porosity of the densified granular system and the mean coordination number, $\boldsymbol{n_c}$ (with coefficient of determination $\boldsymbol{R^2}$ = 0.9894):

$$n_c(\varepsilon) = \left[\frac{-\ ln(\varepsilon - 0.1672)}{0.1495}\right]^{0.9039} \tag{3}$$

As far as screening is concerned, Milhomen (2013) and Milhomem and Luz (2012), highlight that, among the methods of solid-liquid separation for reuse of the water in the mineral processing the screening is an option that cannot be forgotten. Also according to Milhomen (2013), screens connected to ore dewatering are vibrating screens that produce a filtered product with low moisture, with values between 10 % to 15 %. In the same way, Keller and Stahl (1994) point out those dewatering screens are common equipment for performing ore dewatering, having characteristics of allowing processing at high rates and low residual moisture. Ettmayr et al. (2000) and Ettmayr and Stahl (2017) studied a combination of vibration screen and capillary suction to reduce moisture content in the bulk. Yu et al. (2020) studied a flip-flop screen to classify the lower 3 mm iron ore particles, under optimized frequency, amplitude, inclination, and feeding ore rate.

The various quotes about the industrial screen above show that this equipment is very important and widely used for size classification and dewatering. Formally, as Iizuka (2006) has pointed out, screens are basically composed of a steel frame (or a kind of steel alloy), also called the screen box, supported by steel springs or rubber cushions. Mechanically connected to the screen box are the oscillatory mechanism and one or more horizontal surfaces (as a rule) containing the openings that perform the classification and dewatering. Bento and Vimieiro (2021) performed dynamic analysis of a vibrating screen, from data collected by accelerometers. These authors emphasize that optimization should be done not only in terms of screening efficiency but should also aim for lower mechanical impact on the equipment and its support structure.

Reports from professionals in the iron ore mining industry indicate that mineral processing on screens is increasingly being done with more difficulty in obtaining results of moisture and sizing control within the targets set by customers, which leads to losses due to low productivity and reprocessing.

One hypothesis about these losses is related to the character interaction between the flow of ore particles and the screen. When considering the screen system and the particle flow as a coupled spring-mass type system, it can be said that there is a possibility this system is not synchronized, because there are several changes linked to this process, such as the amount of mass on the screen at a given time. There is even an evolution of the moment of inertia of the particulate bed during the progress of interstitial fluid drainage, as the material moves over the screen deck.

Silva e Macau (2012) mention that the synchronization of a conjugate oscillatory system occurs when these are equalized at the same levels of frequency and amplitude. So that the oscillations have similar periods.

Pourmahmood et al. (2011) point out that various uncertainties and external disturbances fall on real dynamical systems. These uncertainties and disturbances are relative to variations in, for example, temperature, voltage, and mutual interference between components. Thus, the synchronization of systems can be broken due to these uncertainties.

In screening depending on the flow conditions and ore characteristics, such as the rate of ore on the screen, particle size characteristics, solid fraction in the slurry, the screen and particle bed itself can be asynchronous. That is, the oscillatory equipment may remain at a given frequency and amplitude, while the bed of particles, or cake, may be oscillating in another frequency and amplitude.

This paper is intended to explore how changing the frequency of industrial screens processing the dewatering of an iron ore bulk influences the final moisture content.

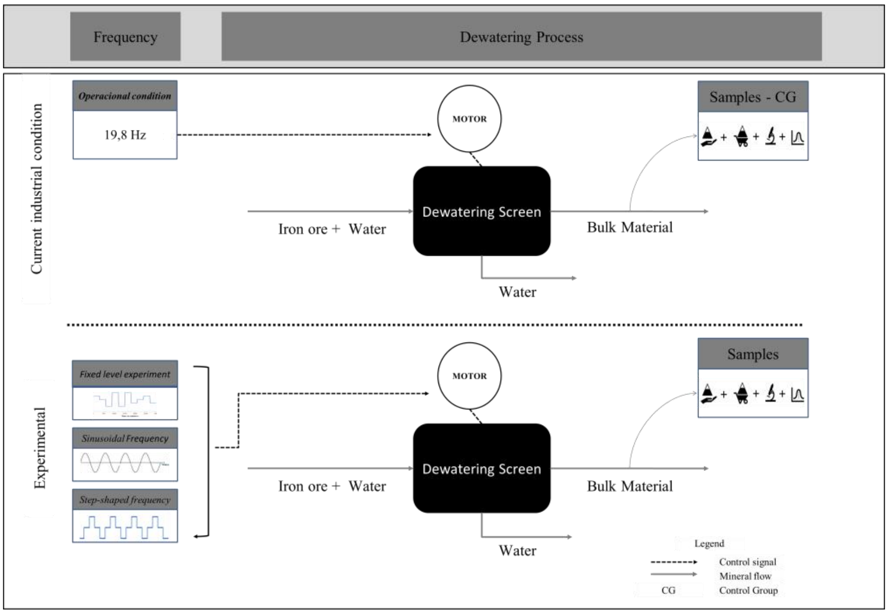
## 2. Methodology

The definition of the research strategy should be based on questions such as the type of research proposed, the degree of control over the phenomenon, and the degree of focus on historical events. The first and most important condition for differentiating between the various research strategies is to identify the type of research question that is pertinent to the research (Yin, 2001). In addition, the research strategy of experimentation is when the researcher can directly, precisely, and systematically change the level of factors of interest in a laboratory or "field" (Yin, 2001). In scientific research, it can be composed of several sequential or concomitant phases: preparation and delimitation of the problem, construction of the research plan, execution of the plan, and preparation and presentation of the report (Koche, 2011).

In the presented work a research was conducted using the strategy of exploratory, quantitative of an industrial experimentation of the dewatering of iron ore phenomenon. For this experiment several experiments were designed and executed in an industrial environment. The main objective was to evaluate how the frequency applied to the industrial equipment, dewatering screen, could modulate the moisture response in the bulk material.

Figure 01 presents, schematically, the flow of experimentation executed. In this scheme it is noted that the controlled factor was the frequency, which was modulated in the experiment in three different ways and compared to the current frequency adopted industrially.

**Figure 1:** Schematic Diagram of the Experiment.




Source: Authors' own elaboration.

### 2.1 Ore samples

Based on several bibliographic references, among which we highlight the one presented by Keller & Stahl (1994), the hypothesis that the reduction of moisture in bulk beds (particle system) depends on the frequency effect and the amplitude. Thus, three industrial scale tests were set up that had as the main factor (controlling variable) the oscillation frequency of the industrial dewatering equipment. In turn, the response of the experiment was the final cake moisture.

These experiments were performed in an iron ore mineral processing plant in the dewatering stage of a granular system with a particle size between 150 μm and 1000 μm. This process is carried out in an oscillating screen with dewatering area dimensions of 4.2 m long, by 1.8 m wide.

In all experiments, samples were taken from the bulk stream after processing (cake). These samples were sent to the laboratory for moisture determination according to the standard aquametric procedure.

Aiming at performance comparison between the tests and the standard industrial processing condition, ore samples were made according to the routine conditions of the equipment, i.e., without any intentional change in the typical dewatering operation. Samples from the typical procedure of the dewatering operation were named the "control group".

One “control group” was generated for the first experiment. For the second and third experiments was generated another specific control group. The second and third experiment had the same control group because those experiments were made on the same day and did share identical ore feed and operating conditions.

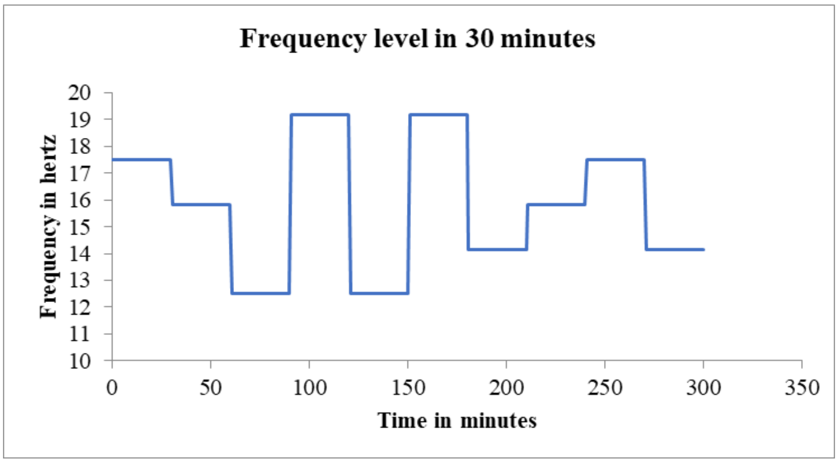
## 2.2 Experimental campaign

### 2.2.1 Fixed level experiment (changing the frequency level every 30 minutes)

For the first experiment, 5 frequency levels were selected at fixed values, which were changed every 30 minutes. To evaluate the result of the moisture response, aliquots were taken every 10 minutes for a selected frequency level.

A random order of frequency levels was determined in this experiment, in order to avoid the influence of consecutive frequencies and ensure the independence of the tests. As replicates were performed for each level, so 10 samples were obtained for this experiment. Table 1 and Figure 2 show the design of experiments used in the first industrial-scale test.

**Figure 2:** Frequency levels changed every 30 minutes.




Source: Authors’ own elaboration.

As can be readily seen, the Figure 1 illustrates the time evolution of the control variable (frequency), in levels with constant set point, during fixed frequency test. In turn, Table 1 explains the corresponding values of the test process parameters.

**Table 1:** Design of experiment for the 30 minutes fixed levels.

| | Variation in levels | |
|---|---|---|
| Assay [–] | Frequency [hertz] | Minimum time at same level [min] |
| *1* | 17.5 | 30 |
| *2* | 15.8 | 30 |
| 3 | 12.5 | 30 |
| 4 | 19.2 | 30 |
| 5 | 12.5 | 30 |
| 6 | 19.2 | 30 |
| 7 | 14.2 | 30 |
| 8 | 15.8 | 30 |
| 9 | 17.5 | 30 |
| 10 | 14.2 | 30 |

Source: Authors' own elaboration.

### 2.2.2 Continuously variable levels experiments

***a) Change of frequency in a sinusoidal form (sinusoidal wave) - second test***

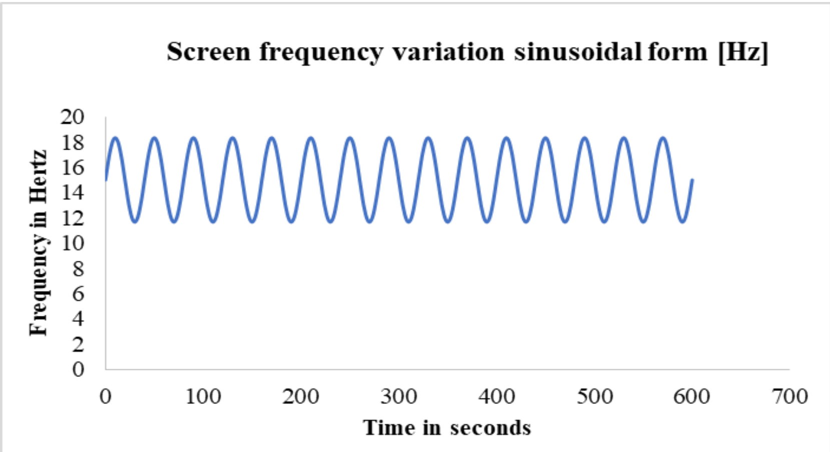
For the test continuous variation of the screen frequency, a sinusoidal equation was defined, as shown below:

$$frequency(t) = h + A * \sin(\omega_0 * t) \quad (4)$$

The terms of this equation are: ***h*** — equilibrium position for frequency [Hz]; ***A*** — established displacement in frequency [Hz]; $\boldsymbol{\omega_0}$ — angular frequency for the phase angle [radian/s]; ***t*** — elapsed operation time [s]. The above function was implemented in the plant control computer and through it changed the frequency of the equipment impeller around the average by 3.3 hertz. Furthermore, the frequency limits were around the equilibrium position that was set at 15 hertz. Thus, the function takes the form below.

$$frequency\ (seconds) = 15 + 3{,}3 * \sin(0{,}157 * t) \quad (5)$$

**Figure 3:** Sinusoidal form of the variation of the impeller frequency.



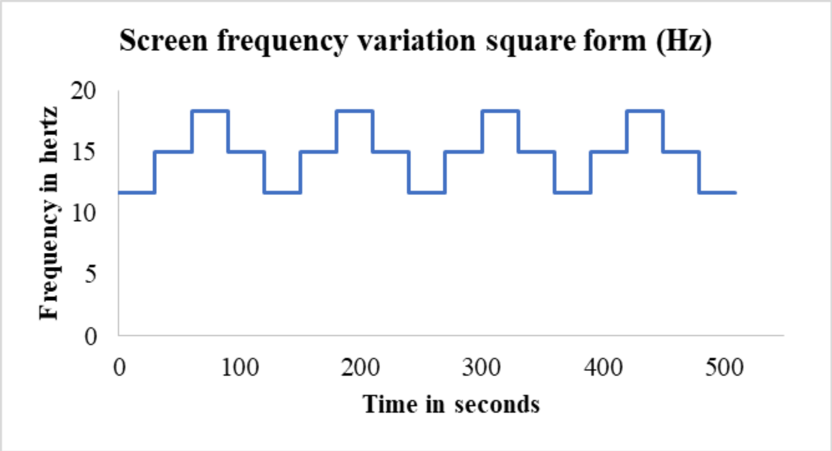

Source: Authors' own elaboration.

The Figure 3 represents the way that the frequency will be variate during sinusoidal test. To evaluate the performance of the experiment on the bulk moisture response, aliquots of the bulk were planned to be taken every 5 minutes. Every 3 aliquots a sample would be formed, the total number of samples for the experiment is 5.

***b) Change of frequency in a periodic step-shaped frequency (square wave) — third test***

In addition to the function presented above, a form of varying the rotation of the screen in the form of a "step" was also tested, that is, every 30 seconds the frequency the screen was changed in level. The levels tested for this form of variation were: 11.67, 15.00 and 18.33 hertz.

**Figure 4:** Variation of the rotation according to the step function (11.67 Hz, 15.00 Hz and 18.33 Hz, at 30 s intervals).




Source: Authors' own elaboration.

The Figure 4 represents the way that the frequency will be variate during stepped test.

As with the sinusoidal shaped frequency change experiment the evaluation of the performance of the experiment on the bulk moisture response was planned by collecting aliquots of the bulk every 5 minutes. Every 3 aliquots a sample would be formed. The total number of samples for the experiment was 5.

## 3. Results and Discussion

### 3.1 Results of the first test at fixed frequency levels

Table 2 shows the final moisture results from the fixed frequency level experiment.

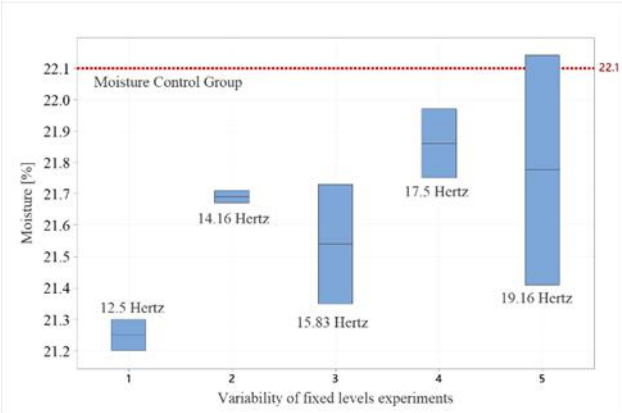
**Table 2:** Laboratory results for the fixed levels.

| Moisture at variation at fixed levels | | |
|---|---|---|
| Test run order | Frequency [hertz] | Moisture [%] |
| *1* | 17.5 | 21.75 |
| *2* | 15.8 | 21.35 |
| *3* | 12.5 | 21.3 |
| *4* | 19.2 | 21.41 |
| *5* | 12.5 | 21.2 |
| *6* | 19.2 | 22.14 |
| *7* | 14.2 | 21.71 |
| *8* | 15.8 | 21.73 |
| *9* | 17.5 | 21.97 |
| *10* | 14.2 | 21.67 |

Source: Authors' own elaboration.

A plot can be drawn for better visualization of the results, from the data above. This is illustrated by Figure 5.

**Figure 5:** Residual moisture results versus industrial screen frequency levels.




Source: Authors' own elaboration.

The Figure 5 shows the moisture results and compares these with the control group result. The control group in this first experiment showed that under the original industrial process conditions the moisture content in the bulk was 22.1 %.

### 3.2 Results of the second test of constant variation of the impeller frequency through the sinusoidal form

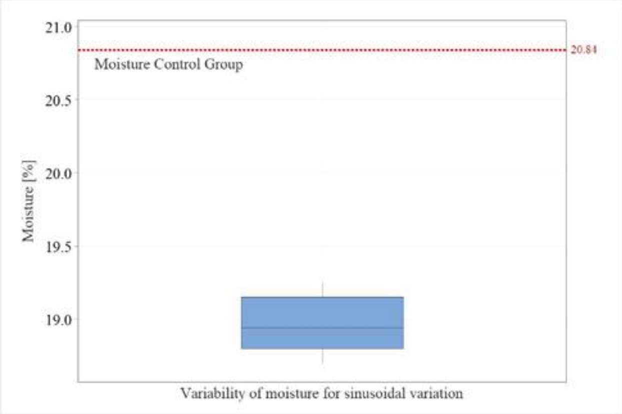
The average moisture content of all samples for the sinusoidal frequency experiment was 18.97 %, with a standard deviation of 0.2%. Table 3 presents the results for all 5 samples collected during the test.

**Table 3:** Results of the experiment with the sinusoidal function applied.

| Moisture Result - Sinusoidal Shape Experiment | |
|---|---|
| *Sample* | *Moisture [%]* |
| *1* | 18.94 |
| *2* | 18.90 |
| *3* | 18.70 |
| *4* | 19.05 |
| *5* | 19.25 |

Source: Authors' own elaboration.

**Figure 6:** Boxplot of the results of applying the sinusoidal shape frequency.




Source: Authors' own elaboration.

Graphically it is possible to observe in Figure 6 the boxplot of all moisture results from sinusoidal test.

### 3.3 Results of the third test of constant variation of the impeller frequency through the stepped form (square wave).

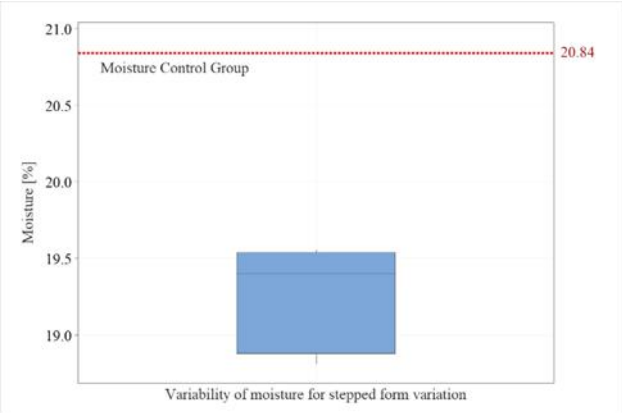
The average moisture content of all samples for the stepped form frequency experiment was 19.25 %, with a standard deviation of 0.34 %. Table 4 shows the 5 moistures determined in the samples.

**Table 4:** Results of the experiment with the stepped form.

| Moisture Result - Stepped Shape Experiment | |
|---|---|
| *Sample* | *Moisture [%]* |
| *1* | 19.40 |
| *2* | 19.56 |
| *3* | 18.81 |
| *4* | 18.95 |
| *5* | 19.52 |

Source: Authors' own elaboration.

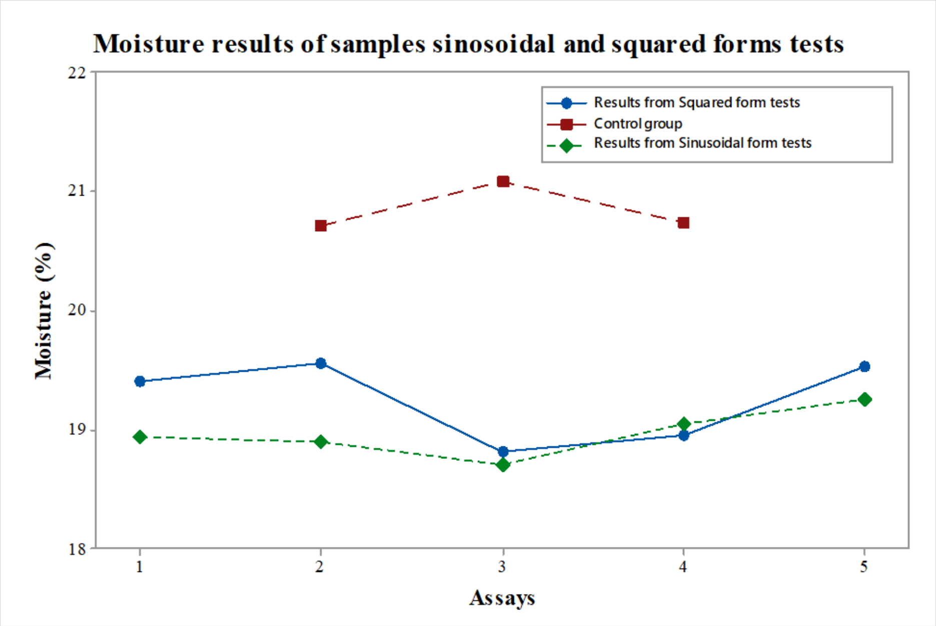
**Figure 7:** Boxplot of the results of applying the step-shaped frequency change (%).




Source: Authors' own elaboration.

The plot in Figure 7 shows the boxplot of all moisture results from stepped test.

**Figure 8:** Moisture results of samples collected at variable screen's frequency by sinusoidal, stepped tests. These conditions were compared with the moisture control group result.




Source: Authors' own elaboration.

The plot in Figure 8 shows the lines for the three test conditions, namely fixed, sinusoidal and stepped tests, with comparison of all these three tests at same moisture scale.

## 4. Conclusion

Reducing the frequency of the screen leads to a reduction in moisture. The sinusoidal cycle of controlled frequency change performed better than the other two modes. This experiment reached average final moisture of 18.97 % with a standard deviation of 0.2 percentage points.

Although the lower frequency of the screen results in lower moisture, a collateral effect was detected during the experiments. This collateral effect is the increased load of ore (mass) on the screen deck. This effect can be counterbalanced by increasing the flow vectorization toward the discharge end, which can be achieved, for instance, by changing the inclination of the equipment. Such a kind of alteration of the experimental apparatus is beyond the scope of this work.

It can be seen that continuous variation of frequency has offered a reduction in average final moisture for the sinusoidal variation mode by up to 1.84 percentage points and for the stepped form the reduction was 1.59 percentage points compared to the samples in the control group (samples taken in the normal operation of the screen).

In addition, it was also verified through slow-motion images that the bulk bed has a different frequency regime than the dewatering equipment. Screen deck tilting (not studied in the present work) will also certainly impact performance. These effects may be studied in future work for better utilization of energy and improvement of the industrial dewatering process.

The way of changing the frequency applied to the oscillatory equipment led to synchronism with the particle system, resulting in a reduction of the ore moisture. Determining the conditions and complementary factors, such as ore type and feed rate into the equipment, influence this oscillatory synchronism will require future works and the respective results may more accurately modulate the dewatering and particle classification processes.

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