New technology for disaggregation and slurrying of Florida phosphate matrix

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Abstract

Phosphate mining represents a significant industry in the State of Florida. In view of the great demand for resources, the industry is in a strong public focus. In mining and processing, the phosphate ore mining process alone is responsible for about 45% of the total energy consumption. Slurry pumping to the processing plant accounts for one third of the energy consumption during mining. Various studies have shown that the optimum solid-water ratio for slurry pumping is approximately 60 wt%. It is difficult to achieve this value with the technology of hydraulic monitor operations applied at the present time. For operational reasons, more precise control of the solids content is almost impossible. The Florida Industrial and Phosphate Research Institute therefore funded this research project.

Disaggregation and slurrying of phosphate matrix represents the principle problem in pumping slurry. It is still state of the art to use draglines in phosphate ore mining. The dragline dumps the phosphate matrix in the pit, where it is slurried with the help of hydraulic monitors and conveyed to a static grizzly. The grizzly is used to scalp larger rocks and roots. It requires cleaning at regular intervals. A suction pump situated behind the grizzly, pumps the slurry to the processing plant. The average solids content of the slurry is only about 25-35 wt%, and varies widely depending on the material properties.

Under this investigation, four different types of phosphate ore were examined. In the first step the phosphate ores were analyzed and characterized. Then two different methods were evaluated to improve the slurrying process. First, tests were performed using high pressure water jets of up to 200 bars in order to disaggregate the phosphate matrix. In principle, it is possible to achieve disaggregation and slurrying using this technology, but the necessary throughput cannot be acquired due to the long retention time required. Second, selective crushing tests were carried out using a wet hammer mill. This technology was able to achieve a solids content of 60 wt%, while still producing a high degree of disaggregation of the clay agglomerates, without destroying the valuable material. A preliminary design for a mobile disaggregation and slurrying unit was developed on the basis of these test results. The new technology could reduce water demand from 2.16 m³/t to only 0.58 m³/t and energy consumption from 1.32 kWh/t to 0.36 kWh/t.

Keywords: Phosphate disagglomeration; High pressure water jets; Hammer mill, Phosphate slurry.

1. Introduction

Phosphate mining represents a significant industry in the State of Florida. The industry is in a strong public focus in view of the great demand for land, water and energy resources. For that reason, it is essential that phosphate industry steadily innovates and improves its extraction and processing technologies. Natural resources will only be preserved through continuous process improvements, while at the same time reducing the vast water and energy needs in phosphate treatment. Phosphate mining alone

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1. Introduction

Phosphate mining represents a significant industry in the State of Florida. The industry is in a strong public focus in view of the great demand for land, water and energy resources. For that reason, it is essential that phosphate industry steadily innovates and improves its extraction and processing technologies. Natural resources will only be preserved through continuous process improvements, while at the same time reducing the vast water and energy needs in phosphate treatment. Phosphate mining alone
is responsible for about 45% of total energy consumption during extraction and processing [12]. In this, transport of phosphate slurry to the processing plant by pumps accounts for one third of the energy demand [2].

The phosphate mining technology has not changed much over the recent decades. In Florida, it is still state of the art to use draglines and hydro monitors in phosphate ore mining. The dragline dumps the phosphate matrix in the pit, where it is slurried with the help of hydraulic monitors and conveyed to a static grizzly. The grizzly is used to scalp larger rocks and roots. It requires cleaning at regular intervals. A suction pump is situated behind the grizzly; it is fed with slurry for pumping to the processing plant.

Various studies have shown that the optimum solid-water ratio for phosphate slurry pumping is approximately 60 wt% [1-2]. However, it is a huge challenge to maintain this value during hydro monitor operation. The average solids content in the suspension is only about 25-35wt%, and varies widely depending on the material properties. In the current practice, more precise control of the solids content is almost impossible. Accordingly, the FIPR 04-069-215 study recommended performing research in this area [2]. The current project intends to contribute to this. Pumping technology for high solid concentration already exists, so the gap between the optimal dragline operation and optimal pumping operation must be closed.

A review of the literature shows that in the oil sands mining, new slurrying systems have been developed over recent years [9]. For example, oil sands mining has seen the emergence of various “at face slurrying” systems. In these systems, roller crushers are used for the disagglomeration of the sticky oil sands bitumen. After that, the material is classified using roller graters or screening machines equipped with spray bars. The optimal slurry density is achieved inside the slurry box by adding additional water with the help of specially designed inlet valves.

A second example of using mobile slurry systems is a chalk operation in Germany [4-5], in which a mobile hammer mill is used for disaggregation of chalk. The slurry is subsequently pumped to a chalk plant.

### Nomenclature

| Symbol | Definition |
|--------|------------|
| IP     | Plasticity index |
| IA     | Activity index |
| m_E    | sample mass at the end of the test |
| m_B    | sample mass at the beginning of the test |
| w_P    | plastic limit |
| w_L    | liquid limit |
| D      | Disaggregation grade |
| T      | Clay content |

2. State of the art of matrix slurrying systems in Florida

Figure 1(a) shows a typical arrangement of a slurrying system for matrix preparation. In the first step, the dragline strips off the overburden and dumps it directly back. Then the draglines selectively mine the phosphate matrix and dump it into the pit. The pit functions as a hopper and works as a buffering system for the subsequent continuous slurry transportation system. Figure 1(b) presents a flow chart.

The hydraulic monitors are installed in the next stage of the process. These systems are equipped with big water guns, which operate with water pressures of up to 14 bars. They have a water consumption of 2,157 m³/h at a feed rate of 1,000 t/h [12]. Their main functions are to disaggregate large clay lumps, suspend the phosphate matrix into slurry and to feed it to the static grizzly, respectively to the pit pump section.

The static grizzly normally consists of 150 mm wide bars in a simple welded construction, mounted in a specially prepared part of the pit. The head of the suction pump is situated behind the grizzly. The static grizzly is used to pre-screen the matrix slurry in order to prevent large stones and roots from clogging or destroying the pit pump suction head. The efficiency of such a process is low because it is only a static process. The water guns must be used to feed the slurry through the grizzly. Given that the grizzly catches stones and roots, it requires repeated cleaning using the dragline or crawler tractors to ensure unhindered material transport.

Finally, the suction pump pumps the suspended phosphate to the beneficiation plant. The slurry transportation system currently operates at 20 – 35 wt% slurry density.
Table 1 shows the parameters of the technology currently used to disaggregate and slurry the phosphate matrix. They specifically refer to the water and energy required to produce one ton of phosphate slurry. Depending on the system, the max grain size is 150 mm as a result of the opening gap in the static grate. A maximum solids content of 30 wt% in the suspension is currently achieved. In most cases, the solids content varies between 20 and 35 wt%. The energy requirement for matrix pumping is 0.62 kWh/t km for a solids content of 30 wt%.

Table 1. Parameters of current operating phosphate slurrying systems according to [2,11]

| Parameter                        | Unit          |
|----------------------------------|---------------|
| Energy consumption disaggregation| 1,32 kWh/t    |
| Water consumption                | 2,16 m³/t     |
| Water pressure                   | 14 bar        |
| Max. grain size                  | 150 mm        |
| Solids content                   | 30 wt.%       |
| Energy requirement slurry pumping| 0,62 kWh/ t km|

3. Analyses of the sample materials

Table 2 summarizes the different test materials and their mass fractions of fine and pebble phosphate. This methodology for fine and pebble content calculation is based on the standard industry method [2]. The mass fraction of plus 1,000 microns and that of minus 100 microns is determined and used to calculate the proportions of fine and pebble phosphates.

Table 2. Overview of sample materials provided

| Sample | Mass content “Pebble fraction” |
|--------|--------------------------------|
|        | > 1,000 µm | < 100 µm |
| A      | 3 %        | 18 %     |
| B      | 10 %       | 9 %      |
| C      | 10 %       | 16 %     |
| D      | 3 %        | 20 %     |

Various soil mechanics tests were carried out in order to characterize the different phosphate samples. In a first step, the water absorption capacity was examined. This represents an index value on the plasticity of the clay minerals; additionally, it indicates the kind of clay minerals [7].

The plasticity is critically dependent on the attraction or repulsion of the clay mineral particles, and in the case of kaolinite and illite, dependent on their particle arrangement. For montmorillonite clays, the plasticity depends mainly on their intergranular swelling [3].
The Atterberg limits (Table 3) describe the water content in the transition from plastic to viscous status (liquid limit \( w_L \)) and from plastic to the semi-solid status (plastic limit \( w_P \)).

Table 3. Overview of clay mineral properties

| Sample | Liquid limit \( w_L \) | Plastic limit \( w_P \) | Plasticity index \( I_P \) | Clay content \( T \) | Activity index \( I_A \) |
|--------|--------------------------|--------------------------|--------------------------|----------------|------------------|
| A      | 28,68                    | 18,86                    | 9,82                     | 2,52           | 4,04             |
| B      | 25,61                    | 21,52                    | 4,09                     | 4,67           | 0,89             |
| C      | 31,67                    | 16,95                    | 14,72                    | 14,72          | 1,43             |
| D      | 34,45                    | 21,37                    | 13,08                    | 13,08          | 1,41             |

The state borders and the plasticity indices according to Casagrande are also shown in Table 3. The plasticity is calculated according to the following equation:

\[
I_P = w_L - w_P
\]  

Another method to describe the plasticity is the activity number \( I_A \). It gives an indication of the type of clay minerals. The actual activity number permits a conclusion on the clay minerals prevailing in the agglomerates [7-8]. Inactive clay minerals are identified by \( I_A < 0.75 \). Normally active clay minerals are in the area of \( I_A = 0.75 \) to 1.25 and active clay minerals are referred to as \( I_A > 1.25 \). The activity number is defined as:

\[
I_A = I_P / (T - 0.09)
\]

Wet sieving was applied in order to separate from each sample the minus 20 microns fraction in preparation for the x-ray phase analyses for clay mineral identification. Tests on their clay mineral content were then conducted. The air-dried material was homogenized and milled in a McCrone-Mill using anhydrous ethanol.

A powder diffractogram was measured and quantitatively evaluated in each case. Then further measurements on oriented preparations were made for further clay mineral identification.

The three measurements were performed on specimens in an oriented, air-dried state, after ethylene saturation and heating to 400 °C and 550 °C. These measurements were performed using Cu radiation in a diffractometer HZG-4 (FPM).

The investigation of the powder samples was performed using an x-ray diffractometer type URD 6 (Seifert FPM) with Co-K\(\alpha\) radiation, automatic divergence diaphragm and a semiconductor detector Meteor 0D.

The phase identification was performed using the analysis tool (Seifert FPM), drawing on the PDF-4 + database, 2011 edition. The detection limits for crystalline mineral phases are in accordance with their structure and the matrix is between 0.5 and 5% by mass. The relative mineral content on powder diffraction was measured using the Rietveld method (program BGMN / AUTOQUAN). Amorphous components were not included and the crystalline components were normalized to 100%. Amorphous components such as iron and manganoxihydroxide or organic components were not considered. The random error (standard deviation) can be estimated as at an absolute maximum of 4%.

Table 4. Overview of clay mineral properties

| Sample | Content <20 μm % | Quartz | Kaolinite | Smectite | Muscovite - Illite | Apatite | Wavellite | Crandallite | Gypsum | Dolomite |
|--------|------------------|--------|-----------|----------|---------------------|--------|-----------|-------------|--------|---------|
| A      | 16.20            | 2.5    | -         | 10-30    | ?                   | 2.5    | -         | -           | -      | 60-80   |
| B      | 9.10             | 3.30   | 13.00     | -        | 11.80               | 47.00  | 5.60      | 15.50       | 3.80   | -       |
| C      | 15.90            | 6.70   | 6.80      | 40.30    | 5.60                | 38.10  | -         | 2.50        | -      | -       |
| D      | 17.00            | 11.10  | 7.10      | 56.00    | 6.80                | 16.10  | 2.90      | -           | -      | -       |

Table 4 shows the results of the x-ray diffractograms. Sample A has a very high dolomite content and the lowest quartz and apatite amount. Sample B is characterized by the highest amount of kaolinite and muscovite-illite exchange minerals. The highest amount of apatite was measured in this sample.

The smectite clay minerals in particular are swellable minerals. This describes their capacity to bind large volumes of water in their structure and that more energy is needed to disaggregate their agglomerates. In this case, the samples C and D should need more energy for disaggregation than sample B. Given the high dolomite content, sample A also belongs to the complex process group.
In Figure 2, the different minerals are classified into five main groups. All clay minerals are included in the group of clay minerals. Phosphate minerals such as apatite, wavellite and crandallite are also assigned to the apatite group. The other important main groups are quartz, dolomite and gypsum.

4. Disaggregation tests with high pressure water jets

Figure 3 shows the high pressure water jet test facility. It consists of the following main parts: sample box, linear bearing with spray bar, time measurement system and high pressure pump. The spray bar slides on a linear guide over the material sample and washes out fine material while disaggregating the agglomerates. The sample boxes have an open gap of 5mm. The amount of disaggregated agglomerates is measured on the basis of differences in mass. The linear guide speed can be varied in the range of 0.3 to 1 m/s. The pump pressure can be modified between 30 and 200 bars.

Following the formula of calculation the disaggregation grade $D$ of the phosphate samples is shown:

$$D = \frac{m_g}{m_B}$$

Statistical experiment design was used to decrease the number of necessary tests. This also facilitates evaluation of the test series. For each test, material with a certain material layer height of between 50 – 100 mm was set up in the sample box. Then the sample box was installed in the test facility. The nozzle pressure ranged from 80 – 140 bar and the retention time from 1 to 4 s. The number of cycles was adjusted between 2 and 6 based on the experimental design. It is necessary to measure the weight before and after the test series in order to calculate the disaggregation grade. Following the tests, the samples were weighed once they had been dried in a drying cabinet. The following evaluation diagrams were then generated on the basis of the data produced in this way.
Figure 4 shows the influence of the material layer height and the nozzle pressure on the disaggregation grade. The disaggregation grade decreases as the material layer height increases. This effect was relativized using higher nozzle pressures.

High pressure water jets can be used to disaggregate phosphate matrix. There is an optimum balance among the main influencing parameters and the disaggregation grade. Figure 5 shows the overall effects on disaggregation. The number of cycles and the retention time especially are responsible for 29% and 26% of the total effects. The nozzle pressure and the type of matrix exert almost equal influence on the disaggregation process.

5. Disaggregation test using a wet hammer mill

Another method of disaggregating phosphate matrix is to use a wet operating hammer mill. In this approach, a hammer mill was modified to include an additional water supply in the mill inlet. The aims of the tests were to determine the maximum throughput, the specific and necessary energy consumption, and the maximum achievable slurry density.
Figure 6 shows an example of the feed material. The maximum feed material grain size was 350 mm. The hammer mill parameters are listed below:

- Hammer mill type: SKET 600 x 370
- Installed power: 9,2 kW
- Number of hammer: 24
- Number of hammer axes: 4
- Gap in the discharge grate: 38 mm

A feed rate of 8t/h was set for each phosphate matrix type. The water supply was fixed at 0.8m³/h. Table 9 shows the results of the disaggregation test series. A slurry density of 60 wt% was achieved for all of the four phosphate matrix types.

The power consumption of the mill is shown in Table 6. The values are recorded from the frequency converter used during the test series. In this, the minimum and maximum values were recorded and then used to calculate an average value.

A sample was taken from each test at the outlet of the mill using a wooden sieving tray with 2 mm openings. The sample was then sprayed with a garden sprayer to remove fine particles adhering to the material. Only the coarser particles and the agglomerates remained on the sieving tray.
Sample A (Figure 7) consists of 80% carbonatic materials, which adsorbs significant amounts of water. During the tests, a part of the discharge grate was covered by sticky material. This means that a greater volume of water is necessary in this case to process this matrix type to prevent failure.

![Sample A](image1)

(a) ![Sample A](image2) (b)

Fig. 7. Sample A after hammer mill (a) and spraying with garden sprayer (b).

Figure 8 shows the results of the tests on sample B. This matrix type was easy to process without any feed material adhering inside the hammer mill. A large quantity of the clay minerals was disaggregated, so that only a small amount of agglomerates remained on the sieving tray.

![Sample B](image3)

Fig. 8. Sample B after hammer mill and spraying with garden sprayer.

The remaining agglomerates have a max grain size of 38 mm. The agglomerates from the slurry system currently used have a maximum grain size of 150 mm. Accordingly, it should be possible to reduce the number of washers at the processing plant, as it is only necessary to remove small clay agglomerates in the washers line. The losses in usable material were reduced due to the total disaggregation of the feed material. The test on sample C resulted in an easy disaggregation of the matrix. After spraying, the largest clay balls remained in the phosphate matrix sample D. In this case, therefore, adjustment of the discharge grate on the hammer mill could improve results.

6. Conclusions and recommendations

The main important result shown here is that it is possible to disaggregate phosphate ore with the help of a hammer mill and to achieve slurry densities of 60 wt%. Figure 9 presents a possible system in the form of a flow chart. The dragline feeds the mined matrix to a feed hopper, where the material is discharged using an apron feeder and conveyed to a roller grater. At the roller grater, the fine fraction is scalped out and only the coarser material is disaggregated in the hammer mill. The hammer mill operates at a low circumferential speed to avoid crushing the pebble phosphate. The fine fraction goes directly into the slurry box. There are currently no plans to separate roots and stones. A frequency converter is used to increase the circumferential speed in intervals in order to crush remaining stones and clean the grater.
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