1. Introduction

In the field of fragmentation, Fives FCB has two flagship machines: the Rhodax and the Horomill (Horizontal roller mill).

The Rhodax was designed to achieve a high reduction ratio, basically from 150mm to 1mm in a closed circuit in a single stage of crushing. Therefore, the Rhodax replaces both secondary and tertiary stages and even the first stage of grinding in most minerals industries in dry or wet processes.

The machine first found its place in industrial applications and especially in very abrasives products which require grinding to –1mm (fired clay, corundum, granite). Then, the field of aggregates industry was investigated and some process advantages were discovered. The Rhodax can be used successfully in silicon metal and the slag crushing industries and will soon be developed for the mining industry.

The Horomill has been designed to grind fine to very fine products in a dry process. The machine’s first market was the cement industry where fine grinding is required for both raw meal mix and cement powders (from a hundred microns to a few microns achieved with our TSV air classifier).

In the meantime, the calcium carbonates and steel slag grinding markets found some benefits in using the compressive technology. More than 56 machines will be in operation by the end of this year. The Horomill can now be installed in dry interparticle grinding applications for the mining and slag industries.

The combination of both these machines offers some full solutions to build complete crushing and grinding facilities.

2. Rhodax

2.1 Genesis

The concept of Rhodax is the culmination of a comprehensive research and development program started in the early 1990’s. The tender specifications were the following:

- A high reduction ratio. The crushing principle combined with the design of the wear liner allows for the reduction of crushing stages. Nevertheless, this principle requires the control of the fragmentation force.
- Control of the fragmentation force. The Power draw by a mechanical system is given by:
  \[ \text{Power} = \text{Force} \times \text{Displacement per unit of time} \]

With the Rhodax, the developed force is known, fixed by the mechanical components. The displacement (i.e. the distance between the liners) varies around the nominal gap according to the material characteristics. In a conventional cone crusher, the displacement is known and varies from the closed side setting (CSS) to the open side setting (OSS). The force is then unknown and depends on the material characteristics.

Consequently, manufacturers of such pieces of equipment are obliged to limit their performance in order to avoid mechanical breakage. In practice, the reduction ratio is limited to about five and the material mechanical properties have to be more or less the same.

- Efficient production of sand. The machine is optimized to produce sands and gravel classes final products. Therefore, it could replace the hammer mill, the cone crushers, the vertical axis crusher, the autogenous grinder, the rod mill, impact crusher and the first chamber of a ball mill.
- Crushing of hard and/or abrasive products.

2.2 Mechanical description

The Rhodax is an inertial cone crusher. The bowl sub-assembly (bowl) consists of a frame supporting the bowl liner. The cone sub-assembly (cone) consists of a structure supporting a vertical shaft and the cone liner. The cone is suspended to the bowl by means of tie rods.
and ball joints (rubber swivels). The bowl is mounted on elastic rubber shoes to filter and minimise the transmission of vibrations to the environment. No extensive civil works are required for the installation of the Rhodax.

The machine’s mechanical drive is not directly linked to the material characteristics unlike the direct mechanical force in cone crushers.

A sliding sleeve on the shaft forms a hydraulic jack. Hence, the cone liner can slide vertically along the cone shaft. The gap between the liners can be adjusted while operating to compensate for wear and modify some process parameters.

2.3 Operating principle
From the top view, the bowl describes a uniform circular motion (horizontal vibration), due to the rotation of two sets of unbalanced masses. Hence, the cone part is also moving in the same way with some different amplitude and phase. A coin lying in a glass which is moved by a circular motion gives a good idea of this principle. The coin is rolling on the glass wall. In the Rhodax, the cone, free in rotation, is rolling on the bed of material.

The four unbalanced masses are synchronised with each other by means of an electronic VSD synchronization called Flux Vector Control. The moving bowl is put into motion by this vibration system and a known and controlled compression force is induced on the material between the vibrating bowl and the cone. The reaction force \( F \) (Newton’s 2nd law of motion) is distributed in the crushing chamber:

\[
F = k mr^2 \omega^2 \quad [2]
\]

- \( k \): proportional factor
- \( m \) (kg): “active” mass of the four eccentric masses
- \( r \) (m): eccentricity of the unbalanced masses
- \( \omega \) (rd/s): rotational speed of the masses

The force \( F \) can be controlled online with this electronic synchronization.

The mass \( m \) cannot be changed for a given machine size. However, these masses have been designed to create a maximum force above the hardest rock known on Earth. One Rhodax is currently crushing some corundum (Bond Work Index = 28kWh/t at 400µm, compressive strength up to 700MPa). Some tests have been performed on martensitic steel balls or hard hematite iron ore as well.

The eccentricity \( r \) is also fixed by the design of the range of equipment.

The speed \( \omega \) can be changed online with the frequency inverters (Variable Speed Drive). A control loop between the power draw and the speed can be implemented.

The moment of the unbalanced masses is also controlled by the Flux Vector Control (FVC: Electronic synchronization). Two masses can move relatively to the first one by means of the FVC system coupled with encoders. This motion can evolve from completely the opposite direction (no vibrations and therefore no grinding effect) to completely same direction (maximum vibrations and grinding force) [Figure 2].
2.4 Process parameters

2.4.1 In bed compressive grinding
This kind of grinding occurs when a layer of material is pinched between the two crushing liners so that the biggest particle size remains significantly smaller than the gap between the crushing parts. The grinding force cannot go through a single grain (mono-granular comminution) but diffused in a collection of grains (bed of material) in which the compactness increases.

The increase of the compactness of a material is a function of the mechanical stress applied to it. This function is also called the “pressure-compactness” relation. The compactness is defined as the quantity (in weigh) of material present in a given volume. It can be calculated as the ratio between the apparent bulk density and the specific gravity. Figure 3 shows the evolution of the bulk density with the use of different types of crushers/grinders. This relation shows three areas:

- The first one corresponds to big rocks and low bulk density. This fraction is typically crushed by jaws crushers (average reduction ratio of 3). For a relative low pressure, the compactness increases quickly.
- The second zone deals with secondary and partly tertiary stages. It increases the compactness; a very low pressure input is required. The evolution of compactness is mainly due to a wider particle size distribution and the arrangement of the grains.
- In the third domain, the pressure required to increase the compactness is exponential. If the material is pinched between two jaws to be ground, only the interparticle grinders can achieve some fragmentation with high pressure applied onto the bed of material.

2.4.2 Fragmentation chamber
The crushing chamber is almost vertical, large at the top and thin at the bottom. In operation, the horizontal circular motion generates a cycle in which both parts of the crushing chamber move towards and away from each other.

During each cycle, the material undergoes the breaking force from one side while it is moving downwards by gravity on the other. The material can move lower in the chamber until the next compression cycle. 3 to 6 grinding and gravity drop cycles happen in one pass through the chamber (multi-compression).

The top part of the chamber is designed to have a big nip and is used to crush. As soon as the material is crushed and goes along the chamber, the bed is formed and the interparticle effect takes place. 20% of the total length of the wear liners is used to grind the bed of material.

In this area, the bed can be subjected to a pressure up to 50 MPa. The material grain size is then reduced in accordance with its pressure-compactness relation. The new PSD and the new arrangement of the particles lead to an increase of compactness (up to 20%).

2.4.3 Power draw
The power draw by a mechanical system is given by the following relation:

\[ P = F \cdot d \] per unit of time \[3\]

- \( P \) (W) : Mechanical power
- \( F \) (N) : Force developed by the system, in this case \( km \cdot \omega^2 \)
- \( d \) (m) : Displacement of the force application point

Except for the stroke, the Rhodax reacts in an opposite manner from the cone crusher for each parameter considered. The most significant difference is apparent when the gap is open, the Rhodax power draw increases.
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2.4.4 Outputs and mass balance

The Rhodax is a volumetric machine. Therefore, the higher the volume crushed, the higher the throughput is. To increase the volume crushed, the gap must be open. The throughput is proportional to the gap setting.

Rhodax throughput in an open circuit: Except for the gap, the grinding force has an influence on the throughput. In fact, the throughput can increase in two ways for a given volume: increase the crushing speed and increase the bulk density of the material.

When increasing the rotation speed, both crushing speed and bulk density increase. We can expect a quick throughput increase. If the eccentricity (phase) is adjusted, only the bulk density increases. In reality, the throughput increases up to a maximum and then collapses.

Rhodax throughput in a closed circuit: The throughput is more or less proportional to the gap. But, it decreases quickly when the speed increases. In the first case, the volume crushed gets bigger and bigger. The number of crushing steps in one pass through the crusher slightly increases with the crushing speed. In the second case, the volume crushed remains constant and the number of crushing steps quickly increases with the crushing speed. As the material is increasingly blocked in the crushing chamber and the increase of speed does not compensate, the throughput decreases [Figure 5].

Rhodax final product output in a closed circuit: Whatever the choices are for the settings parameters (speed [ω], gap [e], phase [B]), the final product output is a single function of the product ω²eB. There are many possible settings to obtain a determined output. But, these settings, separately, don’t have the same effect on the circulating load, throughput and final product PSD. This makes the optimisation of the machine quite flexible [Figure 6].

2.4.5 Specific energies and substitution ratio

Rhodax specific energy in an open circuit: Although the throughput has a maximum, it is not the case for the specific energy. In fact, the power draw increases suddenly. At that point, the crushing pressure is enough to enter the “in bed compressive grinding” zone. Besides, the reduction ratio also increases suddenly. This passage is clearly shown on the second graph in Figure 7 where the specific energy reported to the –1mm production is plotted.

Rhodax specific energy in a closed circuit: Calculated with the throughput, the specific energy increases similarly to the open circuit. But, calculated with the final product output, it is constant. This is specific to interparticle crushing machines and is then the way to scale-up such types of crushers and grinders.

Rhodax substitution ratio in a closed circuit: In order to estimate the grinding specific energy, Fives FCB uses a ball mill batch test. The so-called FCB-Index simulates the specific energy demand for a perfectly optimized ball mill. The substitution ratio indicates the energy savings:

\[
\frac{SE_{FCB-Index \ BM}}{SE_{Machine}} = \frac{\text{Specific Energy measured with the ball mill batch test}}{\text{Specific Energy measured during a machine test}}
\]
In Figure 9, $p_{in}$ has been increased by means of a speed increase. The substitution ration (energy savings) compared to a ball mill increases to up to 1.6 (40%) for the same screening sieve size (630µm).

2.4.6 Particle size distribution
Rhodax throughput PSD in open circuit: The higher the speed, the finer the PSD throughput. This is realized with a constant gap setting. Figure 10 shows a test performed on fired clay with a 10mm gap.

The top size of the PSD depends on the machine size because the machines are designed for a nominal gap. For instance, the gap is 12mm for a Rhodax 300mm and 40mm for a Rhodax 1000. So, it is not possible to produce a (0-25mm) with a Rhodax 300, but it can be done in a closed circuit with a Rhodax 1000 or in an open circuit with a Rhodax 600.

Rhodax throughput PSD in a closed circuit: For the same gap and screening sieve size settings, the final product PSD can be modified by means of a grinding force increase. Figure 11 shows the PSD modification of a –1.7mm coke product when increasing

![Figure 10](image10.png)

*Figure 10 Evolution of PSD in an open circuit vs. speed increase, test performed on fired clay.*

![Figure 11](image11.png)

*Figure 11 Evolution of coke PSD in a closed circuit vs. speed increase.*

![Figure 12](image12.png)

*Figure 12 Limestone PSD in a closed circuit vs. screen sieve size.*

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the speed. Because the grinding force is controlled, the production of fine particles (<100µm) is also under control and can be optimized.

The way to control the product top size in a closed circuit is not the gap adjustment. The screening sieve size choice controls the top size. Figure 12 shows some results obtained on limestone with different screen panels and the same machine settings.

2.4.7 Screen aperture
Screen aperture versus final product output: From ~1mm screening sieve size in a closed circuit to the open circuit, the output is directly proportional to the sieve size (in an open circuit, we consider that the gap is the screen sieve). Below ~1mm, the production is less than expected. The efficiency of the machine drops and becomes less than that of grinders (ball mill, Horomill) under 100µm. The Rhodax finds its optimum in a closed circuit with a ~1mm screen panel.

The circulating load increases suddenly below ~1mm. It is important to underscore that the circulating load is not that important compared to the cone crusher. It has almost no effect on the life of the wear liner because most of the grains are being crushed against one another. The circulating load also remains constant during the life of the wear liners. Lastly, most of the time, the Rhodax replaces 2 or 3 stages of crushing. The global circulating load is lower in the Rhodax compared to the sum of circulating loads from the 2–3 replaced machines.

Screen aperture versus final product PSD: The PSD is very similar to that of the cone crusher. But the cone crusher finer final product is maximum ~6mm (CCS = 6mm). The Rhodax can not only produce coarser final products (~6 to ~40mm) but also takes its full potential by producing (~1 to ~6mm). On abrasive and/or hard materials, the Rhodax is the solution for finer products (~300µm to ~1mm).

Screen aperture versus substitution ratio: The substitution ratio increases with the screening sieve size. According to Figure 15 and many other industrial results, the Rhodax becomes advantageous with a final product P80 above 100µm. For finer products, the ball mill is more efficient in terms of energy savings. Nevertheless, for that range of products, Fives FCB has developed the high pressure roller grinder Horomill which enables to achieve additional energy savings, up to 50%.

2.5 Process improvements
2.5.1 Differential grinding
The control of the grinding force also increases the differential grinding. The differential grinding occurs when the matrix of the material is made up of components with very different grindability behaviours. For instance, Figure 16 demonstrates the differential grinding of chalk with flints. To remove 90% of the flint, the product is ground and screened to ~1mm. The grinding energy is essentially used to grind the chalk rather than the flint.

In the mining industry, this is often the case. The best example is the crushing of kimberlite (soft to medium hard matrix) with diamonds (hard crystals).

2.5.2 Flakeness index (cubicity)
The interparticle principle of fragmentation induces some cracks along natural grain boundaries and weaknesses. The rock cracks under pure compressive stress according to rock mechanics laws. The angle of breakage of the material is therefore around 35–40°. These combined effects lead to cubical particles.

The shape of the particles has some influence in a lot of processes. Decreased friction leads to a lower transfer time (pneumatic vessels, hoppers, trucks loading and discharge). A better flakiness index increases roads’ quality and prevents from the creation of potholes (aggregates industry).

2.5.3 Ore liberation
The liberation of ore is closely linked with the downstream process used to recover it. The recovering facility can require the full liberation of the crystal (DMS) or simple access to the crystal (chemical reaction). The interparticle compressive grinding creates both liberated grains and deep cracks initiated along the natural boundaries in the rocks. As such, the chemical fluid can reach the ore located along the cracks most of the time.

3 The Horomill and its TSV
3.1 Genesis
The development of the roller press (HPRC) proved the interest of compression grinding from the energy savings point of view with respect to the ball mill. Fives FCB developed its own HPRC and carried out some tests. The results were the following:

- The compression grinding process leads to specific energy values markedly lower than the ball mill, even when optimized. The substitution ratio (see 2.4.5) varies between 1.5 and 2 for cement.
- The substitution ratio increases with the fineness. The nip becomes less stable and the circulating load increases proportionally to the fineness. It must be noted that the important increase of the circulating load (more than 12 in HPRC integral process on OPC cement) deals with a significant modification of the final product PSD.

![Figure 13 Final product and circulating load vs. screen sieve size, test performed on fired clay.](image1)

![Figure 14 Final product PSD vs. screen sieve size, test performed on fired clay.](image2)

![Figure 15 Substitution ratio vs. P80 (variation by means of screen sieve size).](image3)

![Figure 16 Differential grinding of chalk containing flint with diamonds.](image4)

![Figure 17 Break on grain boundaries and its consequences.](image5)
For reasons related to the nip dynamics, the grinding speed is limited. Close to this maximum speed, vibration problems often occur.

The high grinding pressure is used to input a maximum work on the material in a single pass and maintain the circulating load as low as possible. Therefore, this pressure does not always correspond to the optimal value. Some materials require less pressure for the optimal grinding efficiency. Moreover, the use of high pressure causes parts to wear and reliability problems.

Investigations were initiated to find another grinding process based on compression in order to keep the energy savings performance of the process while grinding the material in several steps to prevent a prohibitive circulating load and grinding pressure. The principle of a cylindrical shell driven in rotation on its horizontal axis, and one or several rollers in free rotation inside seemed to be an interesting concept. The Horomill and its multi-compression in-bed grinding with moderate pressure process were born.

3.2 Mechanical description and operating principle

The Horomill is a horizontal grinding mill with a roller designed for the integral grinding of cement, or ores. It is especially adapted to all the cases of fine grinding in the dry process.

A cylindrical shell with a horizontal axis rotates above the critical speed by means of a unit gear, pinion, reducer and engine. A roller laid out in the shell ensures the grinding. The material to be ground, centrifuged, undergoes a multiple and controlled compression between the roller and the shell’s grinding track.

From a mechanical point of view, the Horomill combines:

- On the one hand, proven components of the ball mill, by the use of a shell supported on hydrodynamic shoes and of a girth gear drive.
- On the other hand, components close to the principle of the roller press, such as rollers and bearings but operating with moderated pressures, four to five times less than the one used with HPRC. Compared to the ball mill, Horomill leads to energy savings from 30% to 50% while offering an increased reliability of the plant with respect to the roller press.

The design of the complete plant, including optimized auxiliary equipment such as the third generation high-performance classifier (TSV™), also contributes to energy savings.
Currently, there are 47 installations operating world-wide, with an installed electrical power range from 200 to approximately 2500kW. The largest installation located at Cerritos, Buzzi Unicem in Mexico, has six Horomill 3800 units with a shell diameter of 3.8 metres each. The combined usage now exceeds a million operating hours.

The biggest Horomill is now in the order book of Fives FCB. This mill will have a shell of 4.4m diameter and 2940kW installed power. It will be installed in Holcim Barroso plant in Brazil.

3.3 Potential applications
Dozens of tests have been carried out on ores and minerals. Some Horomill machines have been installed for fine grinding of calcium carbonates and sulphates. The Horomill is also successfully used to grind all types of cements, blast furnace slags and cement raw mix (80% limestone and 20% clay with 3%-10% moisture).

The machine is now ready to be installed in the mining industry in the following conditions:
• Dry process. The feed can be wet (up to 10%) and dried with a flash dryer installed underneath the TSV air classifier.
• Fine grinding ($P_{80}$ from 15µm to 100µm).
• Pilot test works. The compression grinding is difficult to simulate and the best scale up involves tests on a small pilot (Horomill 800).
• Preliminary scope of economic ratios (Capex and Opex) related to wear, energy savings and process benefits.

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