THE INFLUENCE OF THE ORE DEPOSIT AND PRODUCT MARKET ON THE DESIGN AND OPERATION OF INDUSTRIAL MINERAL PROCESSING PLANTS

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INTRODUCTION

The mining industry is divided into mineral commodities that include metals, non-metallics, mineral fuels, and structural materials. Metals, both base and precious, are the most widely recognized, and include the sulfides such as sphalerite (Zn), pyrite (Fe), cerussite (Pb), and chalcocite (Cu), and the native metals gold, silver, platinum, etc. Mineral fuels include coal and oil sands, and are defined as implied - mineral resources that supply a raw energy source. The non-metallics and structural minerals are commonly referred to as industrial minerals, designating rocks used in industry.

The most common and abundant of the industrial minerals are the structural materials, which include sand, gravel, clay, and stone of various kinds. These construction minerals exceed all the metal and mineral fuel tonnage combined, and are typically low unit value. The industrial minerals to be addressed in this paper can be defined as any naturally occurring mineral or rock used as a raw material or additive in a range of manufacturing industries, such as paint, electronics, foundries and metal casting, paper, plastics, glass, ceramics, etc.

Over 200 minerals have been defined as belonging to the industrial minerals grouping, excluding the construction and structural minerals. Product markets can be as diverse as the groupings, in some instances becoming highly technical, requiring unique sales and marketing strategy and expertise.

Because the industrial minerals sector is so diverse, both in terms of mineral types and markets served, it is often found to be the least understood. It is near impossible to define, identify and develop economic, technical, and marketing characteristics in generic terms that would apply across the board. For these reasons, a general understanding of the industry is not enough to define the full potential, or avoid the hazards, of bringing a promising deposit into production. A working knowledge of the critical mineral characteristics and corresponding markets are necessary to make an industrial minerals venture a financial success.

GENERAL PRODUCT CHARACTERISTICS

Before the design and operation of an industrial minerals plant, it is imperative to understand the industry. In most cases, design parameters and processes employed for the beneficiation are dependent upon a specific marketable product and the quality of the mineral in the deposit. The importance of this fact cannot be under estimated.

Quartz is a prime example. In a sand deposit, a multitude of economic markets might be identified. If the deposit is located near an urban area and the sand quality is acceptable for construction purposes, such as concrete, markets within 10 to 15 miles should be targeted. Processing costs (crushing and sizing) would be minimal and the selling price of $3 to $5/ton plus any delivery costs would be attractive. If the sand can be processed into a glass grade product through flotation and/or magnetic separation, the sand could sell for $20 to $25/ton if there was a glass manufacturer within 150 miles or so. Yet again, if the sand is of exceptional quality and could be processed into the high and ultra-high pure grades, the quartz could be shipped anywhere in the world with pricing of $500 to +$10,000 per ton.

Although product specifications are very specific for any given industrial minerals market, several general factors apply to the majority of products as follows.

Ore Characteristics/Product Quality

The industrial minerals industry produces a commercial product that remains a mineral and is sold directly to a consumer on individual contracts or sales agreements. In contrast, the final product in the metals industry is normally a metal produced from the host mineral and is sold at published prices in the open market. Combine this with the fact that industrial minerals can be highly variable from one deposit to another, and natural ore characteristics become highly influential in determining market value.

Mica is an excellent example. Not all mica found in nature has equal economic value. Two mica concentrates can have equivalent concentrate grades, but because of the natural characteristics of the mica, can have drastically different market values. A mica suitable for wet ground products with low bulk densities will demand a much higher price than a mica deemed acceptable for dry ground products only.

It is important to determine these characteristics early in the evaluation programs, as these characteristics will influence the plant design. Mica suitable for the wet ground market must be concentrated without the use of chemicals, and therefore must be of a particle size amendable to these processes. In contrast, dry ground mica can be concentrated by flotation, and the design engineer must recognize these facts and reflect such in the final flowsheet.

Mineral characteristics that will influence product quality and the value and marketability of industrial mineral products include the following.

Particle Size: Particle size of the industrial mineral product is not defined for liberation purposes but rather to meet market specifications, and grinding circuits must be designed accordingly. For instance, if an ore requires a 100 mesh grind for liberation purposes, but the market calls for a 30 x 200 mesh product, the material cannot be sold.

Particle Shape: The shape (round or angular, platy, fibrous, etc.) of a mineral can define a market and mineral value. Wollastonite with a high aspect ratio demands a much higher price than those with low aspect ratios. Therefore, it is imperative that the plant design utilize unit operations that will maintain this property. If the wollastonite is not suitable for high aspect ratio uses, more conventional, and less costly, methods can be employed.

Color: Color becomes a critical factor in many industrial mineral markets. Kaolin, mica, limestone, feldspars, etc. can become more valuable with increasing whiteness. Whiteness may be dependent on the ore characteristics (impurities contained within the crystal structure) and beneficiation may not be able to improve the final color.

Chemical Composition: Because of the high variability found among industrial mineral deposits, chemical composition plays a role in value and marketing strategy. Feldspar can be classified as soda or K-spar, depending on the natural chemical composition. This will define the available markets and pricing.

Market Demands

The size of industrial mineral markets tend to be more restrictive and limited than those in the metals industry because the markets are more specific and directly connected with the consumer. The use of fillers is expanding into plastics in automobiles, and fertilizer markets are cyclic due to weather and world economies. Variable market conditions may be tonnage related, or apply to quality, and new industrial technologies can rapidly alter a market.

Therefore, the design and operation of the industrial mineral plant must be flexible to adjust to the variations in the market demands. In addition, an experienced and knowledgeable sales staff capable of recognizing and responding to the markets should be included in the cost evaluation, as process technology and marketing cannot be separated in the industrial minerals industry.

Location

Because industrial mineral operations are often high volume with low priced products (i.e.; construction materials), the geographic location of the deposit can become an influencing factor with transportation costs of the product to the market having a major impact on the deposit's economics. In many cases, the cost of transporting bulk solids can exceed those of mining and processing, and a thorough evaluation will include these factors. The investigation should determine if a rail spur is near, if the material could be transported by barge, or if trucking will be required. Current rail costs should be reviewed, as these can vary from location to location, and from commodity to commodity. The cost structure of rail transportation can be very complex.

Product Consistency

All manufacturers, regardless of the industry, expect and demand consistent product performance from its suppliers. The same holds true for industrial minerals, particularly when attempting to enter a market with a new, unproven product.

Glass manufacturers present a great example. Glass is produced from large mixed batches of various raw materials (silica sand, limestone, feldspar, etc.), and the formulation of the batch is based on the chemical composition and physical properties of these raw materials. Batch formulations, as well as product specifications, will vary from producer to producer, and any variation in the quality of the raw materials can create serious and expensive problems in the glass maker's operation.

However, the glass industry, as with most industrial minerals consumers, is extremely competitive and willing to evaluate and test new raw material sources, especially if a cost advantage can be negotiated. Glass manufacturers may consider changing their formulation if a new product represents a significant cost reduction in their raw materials. Therefore, industrial mineral suppliers must go out of their way to insure consistent product quality, and must establish reliability with a client before a long term sales contract can be solidified.

By-Products

The profitability of many industrial mineral ventures are often dependent on the production of by-products beyond the primary product. For instance, many feldspar producers not only supply the spar, which is their bread and butter product, but may also produce mica and quartz for other industries. In most cases, these potential by-products must be removed during processing to meet the specifications on the primary product, and establishing markets for such products can add significantly to the bottom line, even if additional processing is required.

As most know, the high pure and ultra-high pure quartz from the Spruce Pine area of North Carolina were developed as by-products from feldspar production, and before the true potential of this quartz was developed, it was either waste or sold as low cost construction material. This is an extreme example where a waste product that was an expense to the company evolved into its primary product and highlights the potential of by-products.

An added advantage of by-product development which is often overlooked but must be included in the cost evaluation is savings in tailings disposal, not only financially but in land requirements. If a company is spending $3.00 per ton on waste disposal, but can develop a product that sells for $10.00 per ton, the true value of the by-product is $13.00 per ton. In this example, failure to include the savings in waste disposal detracts from the true value by almost a third, which can be significant in offsetting beneficiation costs or presenting an advantage in sales negotiations.

EVALUATION AND PRODUCT DEVELOPMENT

The test program implemented in any evaluation project is determined by several factors. The material to be tested could be from a new, unexplored deposit, or could be from an existing operation seeking to develop a new market, or create a value added product.

In the case of developing a new or value added product, much is already known about the material, and the evaluation may be as simple as characterizing the product to determine if it can meet imposed specifications for the targeted market. Some process development may be necessary if the material requires modifications to conform to the specifications.

In the case of an unexplored deposit, the evaluation becomes more complex. Often not much, if anything, is known about the deposit, and the development could require a multi-stage project, including several stages of bench testing, followed by pilot plant testing, and eventually flowsheet design and plant construction.

Bench Testing

Bench testing of a previously unexploited ore body begins with a preliminary program in which the feed is characterized and initial beneficiation tests are conducted. Caution must be exercised in obtaining a representative sample for any development program. It should be noted that it is never too early to begin investigating markets for any potential products, as well as shipping options and associated pricing. Good efforts in this area early in the development program can pay tremendous dividends down the road, particularly in establishing good relationships with possible consumers.

Feed characterization includes chemical analysis, mineralogical examination, and particle size distribution of either the feed as received, or crushed ore, depending on the nature of the deposit. Chemical analysis and mineralogical data allow identification of the minerals present, leading to identifying potential markets. The size distribution gives an idea to grindibility and examination of the size fractions will indicate liberation size. The latter is critical, as in most industrial mineral applications, mesh of grind is defined by product specifications and not ore properties.

Preliminary beneficiation tests are conducted to identify the primary product, determine how the material will respond to various processing techniques, give some insight to possible markets, allow the process engineer to become familiar with the material, and produce products on a small scale at relatively low cost. In most cases, the focus is to produce the highest grade product possible, while yields are secondary. Obviously, a working knowledge of the markets and pricing, product specifications, and process costs are essential to properly assess resultant data, draw accurate conclusions, and make appropriate recommendations.

Assuming the preliminary testing has been successful (i.e.; suitable product can be made, processing is reasonable from a cost standpoint, product yields are acceptable or can be improved, etc.), follow-up bench testing is recommended. The objective of this phase should be optimizing the process in terms of product grades and recoveries and costs. A small amount of concentrate may be produced and submitted to potential customers for feedback. The possibility of producing secondary, or by-products, is studied in detail, although an experienced engineer will have a good feel for by-products from the initial testing.

Although the preliminary and follow-up testing can be performed in a single stage, the resultant data should be accurate and complete enough to begin a reasonable economic feasibility study. This should include both operating and capital costs, current product pricing, and other incidentals such as environmental permitting, tailings disposal, and air and water treatment when applicable.

PILOT PLANT TESTING

Pilot plant testing is the next step in the process development. This stage proves the bench process on a continuous basis and provides important scale-up data, such as more exact equipment and water requirements (percent solids, retention times, etc.). Process variables can be investigated, allowing the optimization of operating parameters and product grades and recoveries. Tailings and water treatment, becoming ever more important in new operations, can be thoroughly investigated, allowing these treatment circuits to be properly designed.

The pilot plant can produce tonnage of product for more stringent market evaluations that are often required by the eventual consumers of the product. It is not uncommon for a new raw material to be required to go through a qualification process performed by the consumer. This evaluation can range from the consumer determining key product characteristics in their own lab to actually utilizing the product on a trial basis in their manufacturing facility. In the latter, several tons of product may be requested.

The pilot plant can provide an excellent training ground for future operators. In industrial mineral plants, particularly if flotation is involved, variations in the operating parameters can significantly effect product quality. Because product consistency is critical, operators should be aware of the key parameters, how to maintain them, and recognize cause and effect disruptions so they can be corrected without major loss of production.

Because finances will be the final justification for proceeding with any development, all bench, pilot plant, and economic data must be reliable, and a lack of experience or proper information can be fatal to the investors. This again stresses the importance of being able to match the raw material to proper markets and processes based on product specifications, ore characteristics, and all associated costs.

PRODUCT SPECIFICATIONS AND PROCESS CONSIDERATIONS

Industrial minerals are used in a multitude of manufacturing industries, from construction materials to ceramics to silicon chips in the computer industry. Companies can vary in size from "mom and pop" type operations to large, multi-national corporations. The products are critical to the industries they serve, and are strategic to manufacturing and developing new products and applications. Each end use of these minerals will carry its own set of specifications that can vary from manufacturer to manufacturer. Add to the mix that all industrial minerals will have highly variable characteristics from deposit to deposit (if not in the same ore body), balancing all the critical factors is often a challenge.

To illustrate the diversity of the markets and how ore characteristics and product specifications apply, several examples of mineral commodities are offered below.

Silica Sand/Quartz

Silica sand is perhaps the most widely used of the industrial minerals. It enjoys a multitude of uses in the market place, all of which carry differing product specifications defined by the individual consumers. The ultimate use of the raw material must be considered in the process development phase.

Silica sand may also be referred to as sandstone, quartz, vein quartz, and quartzite. Although there are subtle geological differences associated with the terminology, this section will deal with silica sand as a group. Common uses, in addition to construction products, include trap sand, fracturing sand, casting sand, glass sand, filtration sand, blasting sand, electronics, opticals, etc.

Trap Sand

Use: Sand used in golf course bunkers.

Product Specs: Critical considerations are drainage, appearance, and consistent play by the golfer from the bunker,. Particle size is the key specification, with the United States Golf Association recommending a sand that lies between 0.25 mm to 1.00 mm, with 75% retained between 0.25 mm and 0.50 mm. This size range has been determined to allow the optimum playing conditions from the bunker. Other quality considerations include color/appearance for cosmetic effect, water permeability and porosity for drainage, and organic matter content.

Process Considerations: Processing will focus on producing the proper size range, and may include attrition scrubbing and washing for clay and silt removal, followed by classification into the specified size fraction. It is doubtful that any sand producer would base their process on this product, as tonnage and pricing would be low and seasonal. Instead, trap sand is usually offered as a by-product, leaving the consumer with perhaps a less than optimum choice, since costs would dictate a local supply.

Fracturing Sand

Use: Used in well drilling, frac sand is pumped at high pressure into subsurface rock to open fractures, thus increasing the permeability of the rock and increasing the flow of oil or gas from the well.

Product Specifications: Key quality considerations include sphericity and roundness of the sand grains, acid solubility, turbidity, and crush resistance. The sand is normally free of impurities, well classified, and composed of rounded grains. Typically offered by the supplier in a range of sizes from 3.5 mm to 0.1 mm, which are well defined and very tightly sized. The final sand can be resin coated for better crushing resistance, minimization of fines generation, superior wetability for pumping, and improved flowback control.

Process Considerations: Ore characteristics are important due to the requirement for rounded grains. Grinding via rod or ball milling should be avoided to prevent creating angular grains. Therefore, the deposits natural size distribution must be favorable to the imposed size specifications.

Processing may include attrition scrubbing and washing for clay and fines removal, followed by classification to produce the required size fractions. Some beneficiation in the form of flotation and/or gravity separation may be required to remove other impurities such as carbonates, feldspars, etc.

Foundry Sand

Use: Foundry sands are used in foundries to make the molds and cores that form the metal castings into a variety of shapes and sizes.

Product Specifications: A foundry sand must be able to withstand high temperatures (1300 - 1700° C), high pressure, allow hot gases to escape from the molds, and produce the proper texture for a smooth casting without reacting with the metal. Therefore, the sand must meet rigid specifications regarding grain size and shape, size distributions, and chemical purity.

The grain size and shape of the sand will effect the rate of escape of gases and the surface texture of the casting. Fines and angular grains can cause plugging in the mold, decreasing the rate of gas flow out, and result in blistering and weakness in the final casting. Angular grains and coarse particles can cause pitting in the casting. Chemical purity focuses primarily on the presence of carbonates, which will react with the acid based binders used to form the mold, resulting in strength loss and higher binder consumption. In addition, other contaminants such as feldspar or mica can cause abrasions and weakening of the metal casting.

Process Considerations: Raw ore characteristics are critical given the shape requirements. Grinding (ball or rod milling) should be avoided to prevent angular shaped grains, so the raw material must possess a natural size distribution suitable for the defined size specifications.

Processing considerations should focus on fines and clay removal through attrition scrubbing and washing, followed by sizing into a product that broadly fits in a 30 x 100 mesh range. Additional beneficiation may involve flotation to remove carbonates, which if present, could increase the ADV, or Acid Demand Value of the green sand. However, removal of too many impurities via flotation could be cost prohibitive if multistages are required. Gravity separation techniques may be applied if mica is present.

Filtration Sand

Use: Filtration sand is used to create granular beds for separating suspended and colloidal impurities from water.

Product Specifications: Requirements for filtration sand are set by the American Water Works Association. The key consideration in producing a filtration sand is uniformity of size with a narrow size distribution. Two imposed specifications relating to the size of the sand are the effective size and a uniformity coefficient. Both are determined by the size distribution of the sand, and no rigorous demands are made on particle shape.

Process Considerations: Because fines can reduce the flow through the sand filter bed, attrition scrubbing and/or washing/desliming may be necessary. Classification through screening to meet the size specifications may be required if the raw material is not characterized by tight, narrow size fractions. Organic and micaeous material may have to be removed if present, but beneficiation may be limited due to cost considerations.

Glass Sand

Use: Silica sand is the most dominant raw material consumed in the glass manufacturing industry, which can be catagorized into glass containers, flat glass, and fiberglass (excluding the high tech/high quality glasses). Each of these divisions utilize a glass formulation tailored to yield specific physical advantages for the intended purpose, and as a consequence, impose various chemical and physical specifications on the sand raw material. These specifications can also vary among the glass manufacturers.

Product Specifications: Although some variation will be found in the defined quality of the sand between the divisions and individual manufacturers, most impose specifications in 4 primary areas:

1) Chemistry
2) Colorant Minerals
3) Size Distribution
4) Refractory Minerals

Chemistry and colorant minerals are the most watched group in the raw material. Most emphasis is placed on the iron oxide (Fe_2O_3) content, since most sand deposits will contain iron. Iron values can range from 0.01 to 0.3% Fe_2O_3, depending on the product and manufacturer. Other oxides that are controlled include chromium, cobalt, and manganese, since they are extremely powerful colorants. Limits on alumina content can also be imposed.

An important note - Most glass manufacturers consider consistency of the raw materials of utmost importance, and will typically define variances allowed for the individual oxides if the sand supplier demonstrates a tolerable consistency.

Particle size distribution is also a critical component of the sand raw material. Glass manufacturers typically dictate a size range between 30 and 140 mesh, although again some variance is found among the glass makers, depending on the melting furnace, firing temperatures, and rate of batch fill.

Most will impose a coarse sand limit to insure complete melting of the sand based on the manufacturing parameters. Specifications imposed on the fine end relates primarily to health concerns associated with the fine silica. (**Note:** The one exception to the above size specifications is the fiberglass industry, which utilizes a silica sand ground to 200 mesh.)

Refractory minerals are of great concern to the glass manufacturer, and are defined as minerals that will not melt in the glass batch, leaving "stones" in the final glass product. Common refractory minerals are chromite, corundum, kyanite, silliminate, and zircon/zirconia. The presence of these contaminants are typically determined by heavy liquid separation at a specific gravity of 2.96.

Although limits imposed on these refractory minerals can be very strict, the glass producers are primarily concerned with those present in the +60 or +70 mesh sizes. Finer refractory minerals will melt out due to their size. The fiberglass industry is again the exception due to the already fine particle size employed.

Process Considerations: Due to the imposed specifications on the glass sand raw materials, the processing flowsheet can be fairly complex or relatively simple, depending on the ore characteristics. Therefore, characterization of the run of mine ore can assist in defining the required beneficiation, and should include initial chemical assays, size distributions, and heavy mineral determinations.

Typical unit operations employed in the beneficiation of glass sands can include sizing and/or grinding, attrition scrubbing and desliming, flotation, gravity separation, and magnetic separation. Electrostatic or high tension separations have been used on a limited basis.

Because shape of the sand grains is not critical in glass making, the sand can be ground to the -30 mesh specification if ore characteristics dictate. However, most glass sand producers avoid this comminution step if possible due to cost, and prefer to screen out any oversize unless the sand is produced as a by-product. The -30 mesh feed is usually subjected to attrition scrubbing and desliming to remove any surface stains (particularly iron oxide), eliminate fines and clays, and to prepare the mineral surfaces for flotation if required.

Flotation is usually employed when the sand contains refractory heavy minerals, as the introduction of chemical reagents to the process stream can complicate permitting and environmental concerns while adding to production costs. The refractories can be effectively removed through anionic flotation utilizing an acid circuit with a petroleum sulfonate based collector, or in a neutral or basic pH with cationic collectors (tall oils/fatty acids).

The acid based flotation has proven more effective, although success has been demonstrated in the neutral/basic circuits utilizing a sulfonate/tall oil blend. If successful, this scheme will eliminate the use of any acids for pH regulation, and can also remove any carbonates that may be present, in which case the use of an acid circuit is virtually impossible for obvious reasons.

Gravity separation can be an attractive alternative to the flotation. Spiral separators have proven successful in reducing the heavy minerals to meet product specifications in instances where the ore characteristics allow. The spirals are typically effective down to 50 or 60 mesh, so the distribution by size of the refractories is key when considering this option.

Magnetic separation can be utilized as a finishing step after the flotation and/or gravity separation, or as a main processing stage without the flotation, depending on the ore characteristics. Dry, high intensity separators that employee rare earth rolls have proven very effective in removing highly and para-magnetic minerals, which may be required to meet the imposed iron specifications. These minerals could include biotite, heavily stained sand grains, and iron bearing refractory minerals. Often a sand producer will use the high intensity magnets to produce a special product and will not necessarily treat the entire plant tonnage.

High Pure Quartz

Although high pure quartz could be included in the section on silica sand, the vast differences that exist in this area versus the more "common" sands dictates separate discussion. The primary difference is product quality, while others include the size of the markets, product pricing, availability of suitable raw material, processing requirements, and plant construction considerations.

High pure quartz products serve the higher end, high tech markets, which include electronics, opticals, semi-conductor, lighting, infrared, specialty glass, fiber optics, and the computer and communications industries. Fused silica, or more correctly fused quartz, are common terms applied to the silica for most of these applications, although they have become synonymous with the well known trade names of Quintas and Iota grade products, produced by the Unimin corporation from their facilities in Spruce Pine, NC. These products are also referred to as high pure quartz (Quintas grade) and ultra-high pure quartz (Iota grade).

Product Specifications: Because of the variety of end uses for the high pure and ultra-high pure products, exact product specifications are difficult to assign, and quality is ultimately determined by performance. In fact, it is often impossible for the consumers of such products to define chemical specifications. However, some typical guidelines can be applied to initially evaluate the quartz and control the process. Typical limits on contaminants are as follows.

High Pure Quartz (ppm)

Fe - 20 ppm max.	Al - 200 ppm max.	K - 80 ppm max.
Na - 100 ppm max.	Ca - 50 ppm max.	Li - 2 ppm max.
Mg - 30 ppm max.	Ti - 5 ppm max.	

Ultra-High Pure Quartz (ppm)

Fe - 1.0 ppm max.	Al - 15 ppm max.	K - 2.0 ppm max.
Na - 2.0 ppm max.	Ca - 2.0 ppm max.	Li - 0.5 ppm max.
Mg - 0.5 ppm max.	Ti - 1.0 ppm max.	

It should be noted that the above do not include all elements that could disqualify a quartz, but are instead listed as a basis for further evaluation. It should also be noted that while many describe the purity of quartz in terms of % SiO_2, these could be misleading, especially in the ultra-high pure grades. A quartz product may be described as 99.999% SiO_2, but still contain trace elements on a ppm or ppb level that could hinder its performance.

In addition to the chemical limits imposed, size specifications have been tentatively defined for the high pure and ultra-high pure products. Although these specifications may vary slightly among the consumers, the products are essentially maintained within a 50 x 140 mesh size range.

Process Considerations: High pure quartz products are typically produced through physical beneficiation techniques, including grinding, attrition scrubbing, flotation, and magnetic separation. The ultra-high pure grades, usually produced from the high pure products, receive additional beneficiation in the form intense acid leaching and chlorination.

Details of the technology are considered proprietary, and little data is available for publication. However, the ore characteristics will play a role in the degree of processing, specific types of flotation that may be required, etc. For example, a quartz to be recovered from a pegmatite deposit versus a vein-type quartz will almost certainly contain different types and levels of various contaminants, and must be beneficiated appropriately.

Comment: The key to any successful high pure quartz venture is finding a suitable raw material. It should be cautioned that basing any judgement of final quartz purity on feed analysis, or data generated from partially or unbeneficiated material could lead to wrong conclusions. Only after the raw material has been thoroughly processed and evaluated can the true potential be conclusively defined.

Mica

Mica, a group of aluminosilicate minerals possessing a sheet-like structure, has become a key industrial mineral due to its physical, chemical, electrical, thermal, and mechanical properties, and enjoys a multitude of industrial applications. Muscovite, a potassium-based mica, is the most common and widely used, along with the magnesium-based phlogopite mica. Phlogopite is usually a darker color than the muscovite, and is therefore used in non-color sensitive applications.

Mica's unique properties include high dielectric strength and uniform dielectric constants, making it an excellent electrical insulator. Its thermal properties include low coefficients of expansion, cold resistance, and is not affected by extended exposure to heat, allowing for high temperature applications. It is practically inert, and possesses high tensile strength, resulting in a high durability. These properties create a variety of markets for mica, which is ultimately determined by the mica's individual properties found in any given deposit, which can be extremely variable.

The majority of the mica consumed is in the form of dry ground and wet ground products. Dry grinding has a tendency to pulverize the individual mica flakes, resulting in more granular shaped powders, higher bulk densities, and lower aspect ratios. The wet ground mica creates more delamination, giving high aspect ratios, low bulk densities, and excellent sheen lubricity.

Common uses of wet ground products include paper applications, cosmetics, rubber coatings, paint and plastic fillers, and sealers. Value added wet ground mica that receives proprietary surface modifications find use in specialized markets, particularly in plastics. Dry ground uses include drilling muds, roofing shingles, joint compounds, and fillers in lower grade paints. Because of the lubricity, or "slip" produced by the delaminating, mica is used as lubricants and replacements for asbestos in applications such as brake pads and clutches.

Almost all industrial applications of mica benefit from the grinding process, which tends to enhance the physical properties of the mica. These properties improve proportionally to the degree of delamination that occurs, thus giving the wet ground products significantly better properties and higher pricing. However, not all mica's are suitable for wet ground products due to inherent physical properties, such as bulk density, brightness, color, slip, etc., and may only find markets from dry grinding. In addition, the economics of wet versus dry grinding can dictate the use of the lower priced dry ground products, provided they possess the desired properties for the application. As requirements become more stringent, such as in composite reinforcement and cosmetics, wet ground micas are essential.

A third micaceous mineral is vermiculite, which is a highly weathered, hydrated boitite or magnesium-based mica. Because of its hydrated chemistry, it possesses unique expansion capabilities and high loss on ignition, transforming the mineral into a lightweight product. Vermiculite is used in various markets, including construction and agriculture, and is marketed according to various grades sorted by size.

Product Specifications: Chemical analysis is usually not of utmost importance to most of the mica consumers, although it is typically determined and listed on product spec sheets. The variation in chemistry between different mica's force both producers and consumers to utilize other properties to evaluate a mica's value.

Properties that are important to consumers (and thus the producers) are the particle size distributions, bulk density, moisture content, free silica content, brightness, surface area, oil absorption values, slip and sheen, and aspect ratios. These properties will ultimately determine the most suitable markets for any mica.

While the majority of the above characteristics, such as brightness, bulk density, chemistry, etc., are determined by standard methods, other properties are more subjective. Aspect ratios, or the relationship between the particle diameter and thickness, are difficult to determine and duplicate. Slip, which is an indication of the degree of friction between individual mica particles, and sheen, or luster, are determined initially by experience. These properties and their suitability for products that rely on them are often not deemed satisfactory without actual testing in the targeted application.

Process Considerations: Mica processing can include simply crushing and sizing with impact type crushers and screens, or can become more complex utilizing grinding and sizing, flotation, gravity separation, and magnetic separation.

Mica susceptible to crushing and sizing takes advantage of the differential grinding characteristics of the mica, employing the concept of reducing associated rock faster than the mica. This allows the harder to grind mica to be screened out as an oversize product. For a deposit to utilize this processing, it should be relatively high grade with coarser mica being the natural occurrence. It has the advantage of allowing relatively dry processing, producing a coarse mica concentrate with no chemicals that would be a good feed for wet ground processing provided it meets specifications. Disadvantages include lower grade concentrates, which could ultimately affect bulk densities, and high losses of finer mica, which would require additional processing for recovery.

Coarse mica (+40 mesh) is often recovered by spiral separation. This processing usually requires some crushing and grinding to liberate the mica from any host rock. The communition circuits should be designed to minimize fines and maximize the production of the coarse flake. This option allows mica production without the use of chemicals at a relatively coarse particle size, again producing an ideal wet ground feed. Often two spiral passes, including a rougher and cleaner, are required to produce mica grades of +90%. Concentrates may be subjected to screening to remove any fine grit to produce the final grades.

Mica flotation can be performed in either an acid or basic circuit. Both utilize amine-type collectors as the primary collector, although the basic circuit reagent scheme is more complex, requiring the use of a depressant (goulac) and other modifying agents such as kerosene and/or DLR, a highly refined tall oil. Flotation in acid circuits employes sulfuric acid as a pH regulator (pH = 2.5 - 3.5), with an amine collector. Fuel oil may be used as an additive to assist in floating coarser particles and where dirty feeds are a problem. In both flotation processes, cleaner steps are employed to produce the required grades, along with a classification circuit to remove any fine grit.

The flotation concentrates are typically used as dry ground feed due to the presence of the chemicals, which are a detriment for the wet ground products. If the mica in the ore is not of high enough quality to serve as a wet ground feed, flotation may be the only process used for concentration. If the mica does produce a quality wet ground product, the flotation is typically used as a compliment to the spirals, allowing the recovery of finer mica. This combination of processing produces concentrates for both wet and dry ground production.

Wollastonite

Wollastonite is a calcium metasilicate with the chemical structure $CaSiO_3$. Its most unique feature is its ability to cleave into needle like crystals, creating a high aspect ratio that is important for many of its industrial uses. As a matter of fact, wollastonite is the only naturally occurring nonmetallic, white acicular mineral. However, it has also found uses in low aspect ratio applications, although pricing is greatly influenced when the high aspect ratio characteristic can be used to its maximum advantage.

The high aspect ratios allow wollastonite to be used as reinforcers in composites and plastics, increasing tensile flexural, and impact strengths. Plastics appear to be its fastest growing application. Other applications include paint fillers, ceramics, asbestos replacements, sealants and caulks, and friction products. Some wollastonite may be surface modified to optimize its performance in composite materials, resulting in stronger bonding, enhanced mechanical properties, and increased weather resistance. Low aspect ratio products find uses in glass,adhesives, abrasives, metallurgical applications, and steel manufacturing. Depending on its use, the wollastonite may be supplied as fine ground products, or in coarser fractions similar to glass sands.

Product Specifications: Wollastonite specifications are market specific. Concentrate grades must be a minimum 90% wollastonite content, with some applications requiring higher grades of +97%. For higher end uses, the aspect ratios must be maintained as high as possible, giving more importance to processing choices.

Particle size distributions are critical on fine ground products, while color, whiteness, oil absorption, and bulk densities can be specified by individual consumers. Maximum iron content (Fe_2O_3) may be specified by certain consumers, although for the most part, these irons can be considerably higher than most "white", high end industrial mineral products.

Process Considerations: The most important processing consideration is creating and maintaining a high aspect ratio, as these products demand higher pricing in the market place. Most producers regard their milling techniques as well as fine grind technology, as proprietary, and guard them closely to maintain a commercial advantage. For production of low aspect ratio products, more conventional milling techniques can be employed.

For beneficiation purposes, the ore characteristics play a key role in the flowsheet design. Because high grade concentrates are required for most markets, the majority of associated gangue minerals must be successfully removed, and unit operations in the beneficiation plant must consider the type and amount of these gangue minerals.

Flotation is used to remove calcium carbonate, which is commonly associated with wollastonite deposits. This is especially critical for plastics applications. Quartz, if present, most also be removed to create the grades, bulk densities, and high aspect ratios. This is also done with flotation, utilizing amine-type collectors in conjunction with depressants and/or modifiers. High intensity magnetic separation is another common beneficiation practice, as many deposits are characterized by the presence of garnets and diopside.

Phosphate Rock

Phosphate rock is defined as a rock material that contains sufficient phosphate values for commercial usage. Grades are characterized by either its % P_2O_5, or by % BPL (bone phosphate of lime), which is a mathematical equivalency calculated from the phosphate content. The most commercially exploited phosphate rock is from the apatite family of minerals.

The most critical and largest of the phosphate markets is fertilizer, as phosphate rock provides the essential soil ingredients required for the agricultural industry. This requires the physical concentration of the phosphate rich minerals from the ore, followed by chemical processing of the concentrate to extract the phosphate. This places phosphate rock in a unique position, as consumption is governed by seasonal weather patterns and regulations controlling it use rather than periods of economic growth and recession, which characterizes most of the other industrial minerals markets.

Other uses of phosphate include the food, beverage, and animal feed industries. Non-fertilizer, non-food applications are found in the production of flame retardant materials, water treatment, textiles, pesticides, and plastics and rubber.

Product Specifications: Product specifications are difficult to quote for the phosphate industry for several reasons. Unlike most industrial minerals, the rock concentrations will more than likely be sent directly to the chemical processing facility for fertilizer and/or acid production.

Because the chemical facilities are essentially extensions of the beneficiation plants, owned and operated by the same Companies, the phosphate rock is not typically sold on the open market, and product specs are primarily for internal purposes. Often, the chemical plants are forced to except whatever concentrates are produced by the beneficiation plants, which can create internal friction amongst management teams. However, some general comments can be made that are defined as critical to the operation of the chemical treatment facilities.

Another consideration is the variability from one deposit to another. Commercial ore deposits currently being mined can run anywhere from 3 to 4% P_2O_5 to as high as 20% P_2O_5. Associated gangue minerals can vary just as drastically, ranging among various levels of silica, clays, and carbonates, as well as other trace mineral contaminants. These factors highly influence the concentrate grades that can be produced.

As a general statement, the beneficiation plant should produce as high a P_2O_5 content as possible for feed stock to the chemical plants. Silica content, or acid insols, in the final concentrate should be low (less than 2.0%). Another important product characteristic is the $CaO:P_2O_5$. If either of these are too high, the performance of the fertilizer and acid plants can be adversely affected.

Process Considerations: Most phosphate operations employee several steps of flotation as the primary beneficiation method. In the case of igneous deposits, some crushing and grinding may be required to reduce the rock to flotation size. Most sedimentary deposits contain phosphate pebble and the ore is typically classified to flotation size without any comminution..

Depending on the type and amount of clay slimes present, attrition scrubbing and desliming may be required ahead of the flotation. This will be defined by the ore characteristics, but typically the sedimentary deposits will contain more troublesome clays. If these clays are not removed, reagent consumption will increase in the flotation, and recoveries of the concentrate will decrease, thus influencing unit costs significantly.

Phosphate flotation is most commonly performed with fatty acid/tall oil type collectors. After conditioning at high solids, a primary froth concentrate is produced to reject the majority of the silica. Often a cleaner of this froth is employed to drop out additional silica. If silica content continues to be high, an additional flotation is required, consisting of a de-oiling step with sulfuric acid to remove the primary collector from the phosphate froth, followed by flotation of the remaining silica with amine type collectors. Both the fatty acid and amine flotation steps are conducted at neutral, or slightly basic pH.

Several major producers utilizing the above process have found it beneficial to split the flotation feed into two size fractions, thus resulting in fine and coarse flotation circuits. The size separation is determined by the ore characteristics and how the various fractions respond to the flotation.

A challenge in the beneficiation of phosphate rock is the removal of carbonates. The fatty acid flotation will float both the phosphate rock and the carbonate, and the amine flotation will not separate the two. Although much research has been done to effect this separation, at present there is no economic method available for most deposits, thus making the carbonate content of the ore an important consideration.

Feldspar

Feldspar is the most abundant of any mineral group, accounting for approximately 60% of the earth's crust. Commercially exploited deposits are of two main types: Orthoclase (or microcline), a potassium based feldspar, and albite, which is a sodium based feldspar. Feldspar concentrates containing over 10% K_2O are classified as potash spar, while Na_2O values above 6% are considered soda spar.

Feldspar is most widely used in the glass and ceramic industries, as well as fillers and extenders in a variety of manufacturing industries, such as paint, plastics, etc. The high alumina values associated with the feldspar are desired for flux purposes in both the glass and ceramic industries, although this is more critical to the glass maker. Ceramic producers, which use feldspar in both body and glaze applications, are typically more concerned with alkali ratios.

Product Specifications: A range of commercial feldspar products are available, but the key specification is chemical analysis. Alumina and alkali values are important for the key markets, as is iron content. For glass purposes, Fe_2O_3 should be below 0.10%. For ceramic purposes, a body spar is generally less than 0.08% Fe_2O_3, and feldspars used in glazes should be less than 0.06% Fe_2O_3. Alumina values are targeted at 18% Al_2O_3 minimum, and perhaps higher for glass applications.

Alkali values will range from deposit to deposit, and consistency is considered extremely important. Most ceramic and glass manufacturers will accept variations in the general specs listed above if the product quality is consistent and pricing competitive.

Particle size distribution is important in all markets. Glass grade spar is sized to 30 x 200 mesh, while body spar for ceramics will carry a specification of a maximum percent coarser than 140 mesh. Feldspar used in glaze is typically finer than body spar, allowing only a small percentage on 200 mesh. Fillers will range from -325 mesh down to micron sizes, and are usually supplied in a range of top sizes.

Other critical properties include fired color and associated minerals for ceramics, and brightness and oil absorption for fillers. Filler grades are often characterized by a Hegman Grind factor, which essentially identifies the coarsest particles present. Average particle size and surface areas are defined for the finer products.

Process Considerations: Most feldspar deposits, originating in pigmatites, granites, or other hard rock ore bodies, require crushing and grinding prior to processing. The final comminution circuit design will depend on the ore characteristics, such as hardness of the host rock, degree of weathering, etc. Grinding circuits are typically designed to reduce the crushed ore to 20 or 30 mesh to meet the glass market specifications.

Flotation is utilized to concentrate the feldspar. The most common, and effective, reagent scheme includes hydrofluoric acid and amine collectors at a low pH (<3.5). Because of environmental concerns associated with the HF, other chemical regiments have been researched, and some put into practice, although none to date have proven to be as effective as the HF/amine combination in regards to grades and recoveries. Dry processing has also been attempted with little or no success.

Although the HF is an excellent activator of the feldspar, allowing for very sharp separations from associated quartz, it also tends to activate mica, biotite, and other iron bearing minerals, which will report with the feldspar froth product. Therefore, any associated minerals must be removed ahead of the feldspar flotation, particularly if they create problems for the anticipated markets. Common practice involves the removal of mica and biotite with standard flotation techniques, and the flotation of other iron bearing minerals utilizing practiced reagent schemes.

Following filtering and drying of the feldspar concentrate, the product can be shipped for glass purposes, or will require additional grinding for ceramic and filler applications. This grinding is performed in air swept mills in closed circuit with air classifiers, and the market will dictate the fineness of the grind. In the case of glaze and filler applications, the coarse glass grade feldspar may be treated with magnetic separators to produce the final iron and color/brightness specifications.

SUMMARY

The design, construction, and operation of an industrial minerals facility is vastly different from a metallic processing plant. Because the mineral products are market driven with exacting specifications, demanding long term sales agreements with clients, a market study and thorough evaluation of the product must be conducted before spending capital to develop a property.

The marketing study is critical, and should be one of the first exercises performed. It should include: 1) a survey of the potential use of the mineral; 2) size of the market; 3) price of the commodity; 4) available transportation and costs; 5) estimates of potential profitability based on the potential products; 6) by-product potential; 7) competition from other companies and/or minerals.

The process engineer must be aware of the general market conditions, product specifications, pricing, and associated costs. It is imperative that the development program characterize the ore, identify the key mineral properties and potential products, and match the beneficiation process to the corresponding markets. The resultant process flowsheet should be optimized through pilot plant testing, producing data for precise cost estimates, tonnage of product for customer evaluations and proving product quality and consistency. Failure to do so will lead to wrong conclusions and costly and erroneous recommendations.