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Towards waterless operations from mine to mill

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ABSTRACT

To respond to the increased demand for commodities, increased volumes of primary ores need to be mined. This could lead to major challenges with water and tailings management since ore grades are low and many mining operations take place in high water stress areas. The current mineral processing methods used are highly water intensive and, consequently, there is increasing interest in finding alternative solutions to produce raw material concentrates using little or no water. Dry separation technologies capable of efficient recovery of commodities are relatively rare and highly dependent on the materials to be separated.

Low-grade complex ores require energy-efficient solutions for liberating material. Controlled optimisation of the rock fragmentation chain from blasting to comminution can be seen as a viable option to reduce the need for energy-intensive grinding. Application of pre-concentration methods to remove barren waste prior to grinding, developing cost-efficient and energy-efficient methods for comminution, use of mechanical or chemical pre-treatment methods for modifying the mineral surfaces and replacing water with solvents for leaching are all good tools when considering the change from wet to non-aqueous processing. Nevertheless, considerable multidisciplinary research, along with many new methods and holistic, innovative solutions are required to enable the change.

1. Introduction

A transition to a low carbon society is a challenge that will require vast amounts of metals and minerals. The easiest-to-mine ores have already been exploited and the remaining ones are typically complex, low grade ores. The ore grades are decreasing but at the same time global production has continued to grow, enabled by new innovative technologies. More inputs in the form of energy, water, capital and labour are required for the same output and at the same time larger volumes of waste are generated (Spooren et al., 2020).

Optimising water usage in industrial processes has become an important part of the improvement of existing operations as well as the design of new projects. Water availability is a big challenge in beneficiation of ores, which is an essential part of the mining value chain for producing metallurgy-ready materials for further refining (Meissner 2021). The consumption of water in the mineral industry can be in the order of 1.5 to 3.5 m^3 of water per metric ton of ore processed (Moreno et al. 2021). A significant portion of metal mining production is concentrated in areas where water stress is already high. The situation is expected to worsen due to climate change and vastly increasing demand for raw materials resulting from the green shift to sustainability. To improve resiliency, it is vital to reduce the water intensity in mining processes.

Due to the decreasing of ore grades larger tonnages are needed to be mined and more water is required to produce the same amount of concentrate. Water management in the concentrating plant can be seen as both environmental and production-related issue (Michaux et al. 2019). Recirculating the process water in the flotation plant is challenged by the quality of water originating from various sources (e.g. tailings ponds, thickener overflow, fresh water, etc.). Along with chemicals deliberately added in the process, the major effect on process performance comes from the ore properties and processing parameters and the quality of water used. Recirculation of water in concentrating plants leads to accumulation of dissolved species, which may have detrimental and often unknown effects on the process performance. One of the main challenges for the efficient water management in the plant has been the lack of suitable and reliable online analyzers that can operate in challenging environment, are low-cost and require minimum

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amount of maintenance. Moreover, there is a need to create platforms that link the quality of process water to the plant performance and to account for the production-related issues when water-saving strategies are implemented. The recent developments made with mineral processing simulation platforms were shown to enable the quantification of such issue (Michaux et al. 2019, Michaux et al., 2020).

The cost associated with mineral processing operations within arid regions remains a major obstacle to the economic viability of such resources (Baawuah et al. 2020a). Moreover, increasing environmental and social challenges and risks related to water and tailings management act as drivers to finding solutions for reducing water in mining operations. Metallic mineral processing operations are typically carried out in aqueous media. However, with the absence of water-related risks such as failures of tailings dams, non-aqueous processing is now considered a better option. As known deposits are of increasingly lower quality, more water is needed to produce the same amount of concentrate, increasing stress on local water bodies and the design of robust water management systems for safety. This "low grade effect" is becoming significant, and actions are now needed to mitigate this, including the incorporation of new and advanced technologies in various areas such as energy production.

Application of dry processing technologies in mineral processing operations is an important area of research at present. Currently, technologies for the efficient dry separation of valuable minerals from gangue are relatively rare. Also, research is required into reducing the high energy consumption needed for dry grinding and resolving the challenges of handling dust. The mineral content of low-grade ores tends to be complex which results in increased energy consumption for comminution to release fine-grained minerals. Furthermore, the efficient and safe handling of fine-grained material across the value chain, from mine to tailings management, poses additional challenges for mine operators. The pre-treatment of ores prior to grinding to reduce energy consumption, and the alteration of mineral surfaces to be more prone to dry or non-aqueous separation, are both research areas of interest.

The European Union (EU) is one of the biggest consumers of nonferrous metals worldwide and its dependence on imported raw materials to produce metals and metal products is growing rapidly (Spooren et al. 2020; Törmänen et al. 2021). EU highly relies on imports of more than 95 % for most Critical raw Materials (CRMs) and is becoming increasingly dependent on the foreign supply of both raw materials and end products. For example, digital technologies and data storage require considerable increases in the consumption of CRMs, such as REEs and palladium, which are mainly produced by China, South Africa and Russia (Eerola et al. 2021).

Taking REEs as an example: In terms of processing of REEs, most of the conventional separation techniques -both wet and dry- have been applied, depending on the ore and mineralogy and chemical and physical properties of the minerals. Typically in these cases there are several REEs in the ore and to recover them a combination of different unit processes is needed (Borges de Lima 2015). Electrostatic separation and dry magnetic separation are often used as part of the combination process, preceding the flotation. Moreover, various leaching techniques -tank, heap and in situ- are used in recovering REEs, for example from the clay minerals (Borges de Lima, 2015).

Conventional route for producing platinum group elements (PGE) includes pyrometallurgical treatment after flotation. Platinum group metals (PGM) are often produced as by-products of base metal (Cu, Ni) processing when the actual separation from the base metals takes place in the smelter. The challenge with some PGE deposits is the fine grain size of the minerals and low sulphur content which challenges the flotation process (Maksimainen et al. 2010). PGM natural resources are very limited and the demand is increasing worldwide (Dong et al 2015). Therefore recovering PGMs from secondary resources will become more and more significant. Recovery of PGM from spent auto catalysts is typically done by hydro and pyrometallurgical routes. However, prior to metallurgical processing the spent catalysts are pre-treated mechanically (crushing, screening). The same applies to the treatment of many other secondary raw materials. For example, separation of various elements for MSWI ash can be done by following common processing routes for primary ores (Kaartinen et al. 2010).

The definition of "fines" is highly case dependent. In quarries, material with a particle size < 4 mm is considered as fines whereas, in mineral processing operations, the meaning is very different. Separation of fine particles (typically < 50 μm) by conventional wet processing technologies such as froth flotation requires special attention, and the presence of ultrafine (<10 μm) particles usually result in inefficient process performance (Leistner et al. 2017). In the *Basics in mineral processing* handbook (Metso 2018), *dust* is defined as particles smaller than 100 μm. Extending non-aqueous processing of ore beyond crushing to the subsequent grinding and separation stages requires a well-controlled method of providing material that is high-quality and has a narrow range of particle sizes to those stages. Inefficiencies in fine particle separation translate into both a large loss of revenue and increased amount of waste. Feed material that is too fine causes major challenges and recovery losses in conventional wet processing and the presence of fine-grained gangue minerals can have a detrimental effect on processing efficiency.

Mining is a series of interconnected processes and so overall performance is best optimised by considering the value mining chain as a whole. A shift from wet to non-aqueous processing requires a holistic understanding not only of the process-related parameters (mineralogy of the ore, available technologies etc.) but also of the preceding mining operations. The *Mine-to-mill* concept – optimising the blasting, crushing and grinding chain – is a good example of wider thinking and how it can improve the sustainability of a mining project (Ouchterlony 2003; McKee 2013). However, to produce optimum quality concentrate for post-treatment it is important to have comprehensive understanding not only of mining value chain but also of the operations beyond: if the post treatment method will follow hydrometallurgical or pyrometallurgical route or what is expected from the feed material and what will be the final application of the industrial mineral concentrate. In any case the quality of the concentrate has a major effect on the further downstream processing and related cost since concentrate treatment charges and smelter returns are highly affected by grades and impurities (Mkhize et al 2011).

From the energy efficiency perspective, it is essential to understand the associated size reduction mechanisms in order to increase efficiency (Napier-Munn 2015). Smart blasting helps to obtain the optimal size distribution to improve downstream processes. Also, improving methods used for crushing fine-grained material is considered to produce a more energy-efficient process than conventional grinding. Preconcentration of dry primary crushed ore using bulk ore sorting or various particle sorting methods, carried out before the energy intensive grinding process, removes gangue minerals and thus reduces energy consumption, fines generation, water consumption and tailings (Lessard et al. 2014). Another aspect that affects the mine-to mill approach and its overall economics is waste valorization and the overall mine-to-mill carbon footprint. Now the circular economy strategy is increasingly seeking solutions for the mining waste, and it is driving the focus towards assessment of its usefulness for new alternative construction products (Murmu & Patel, 2018; Veiga Simão et al., 2021; Cobîrzan et al., 2022), or materials such as geopolymers and ceramics (Komnitsas & Zaharaki, 2007; Kiventerä et al., 2018) and as a source for metals and minerals to enable the green energy transition (European Commission (EC), 2020; International Energy Agency (IEA), 2021, Whitworth et al. 2022). The circular economy approach is not alien to the mining industry that in practice makes assessment about the value and the fate of the mining waste through feasibility studies and closure plans. For the comprehensive valorization of the mining waste, several factors must be considered such as product value-chain, design options, environmental impacts, and trade-offs between the benefits and costs of adopting the circular solutions (Kinnunen & Kaksonen, 2019; Araya et al., 2020; Drif et al., 2021). The path towards repurposing or reprocessing of the mining waste is only viable when the technological readiness level has reached tangible maturity, but until then the industry must apply duty of care (Boswell & Sobkowicz, 2011) and best practice to manage it either by containment in waste deposits (e.g., tailings storage facilities) (Garbarino et al., 2018; ICMM et al., 2020) or reuse in their operations (e.g., mine backfilling, dam rockfill, road sub-base).

This work considers a chain from mine to non-aqueous mineral processing operations, with a special focus on management of fine-grained (<50 μm) material (Fig. 1). The objective is to provide an overview and some selected examples of potential methods for energy-efficient production of valuable materials from complex ores, consider ways of mitigating waste from the mill feed, and examine the main methods for waterless processing of minerals and management of tailings. Due to the vastness of the subject, the focus is merely on the methods in general and the material transportation is ignored from this paper.

2. From mine to separation of fines by non-aqueous methods: An overview

Comprehensive management of fines (particle size typically<50 μm) plays a key role in non-aqueous processing. When handling dry ground material, dust is a challenge to overcome as is the presence of fine-grained gangue minerals, which often have a detrimental impact on the separation efficiency. Low-grade, disseminated complex ores need to be sufficiently reduced in size to release the valuable materials but, at the same time, in order to improve process performance, it is vital to prevent formation of an excessive quantity of fine-grained material (especially gangue) since the energy required for grinding increases exponentially with product fineness (Little et al. 2017). The more effectively the size reduction can be carried out in the preceding operations (blasting, crushing) and the better the waste is removed from the mill feed, the less energy is needed for actual grinding.

There are fewer methods for efficient dry separation than for wet processing. The main techniques applied include ore sorting, gravity, magnetic and electrostatic separation. For non-aqueous processing, replacement of water by chemicals such as organic solvents – solvometallurgy – can also be considered (Binnemans et al. 2017). The efficiency of dry processing techniques is strongly related to the properties of the materials to be separated. The pre-treatment of ores or mineral surfaces prior to dry separation can be beneficial in improving the recovery and quality of the concentrate in certain cases (e.g. Yu et al. 2019, Yuan et al. 2020).

There are several issues to be taken into account towards waterless operations and it is vitally important to have a comprehensive understanding of the consequences when adopting new technologies or processing routes. In some cases the new alternative may lead to the higher carbon footprint (e.g. use of some solvents to replace water or when recycling/ processing of secondary raw material is environmentally more harmful than production from primary sources).Handling, transport and disposal of dry or waterless fine tailings can be a challenge due to dust. Experience of paste tailings and dry stacking of tailings is useful for most efficient handling of the fine material after waterless processing.

2.1. Ore characteristics

There is a need to maximize resource use efficiency by extracting maximum value from mined products. To optimize resource efficiency, reduce technical risks and environmental impacts, comprehensive understanding of ore variability and mineralogy is of utmost importance: the fundamentals for any processing of treatment of ore and tailings are initially dictated by the mineralogical and chemical characteristics (Dominy et al 2018, Peltoniemi et al 2020, Quast et al 2017, Mkhize et al 2011, Lotter et al 2017). The more complex and disseminated ores require more intense grinding to liberate valuables for processing. Selection of processing route is among the main technical decisions to be made in mine planning. Integrating mineralogy-based analysis early in the project development enables to generate good understanding of the behavior of material through process flowsheet options.

The most critical single item in process design is understanding the feed material the plant will be treating: what is the mine going to send to the mill and how do each of the feed types react metallurgically. The key property of interest is the grade of the valuable mineral(s) as it directly influences the revenue from saleable material. However, it is as vital to

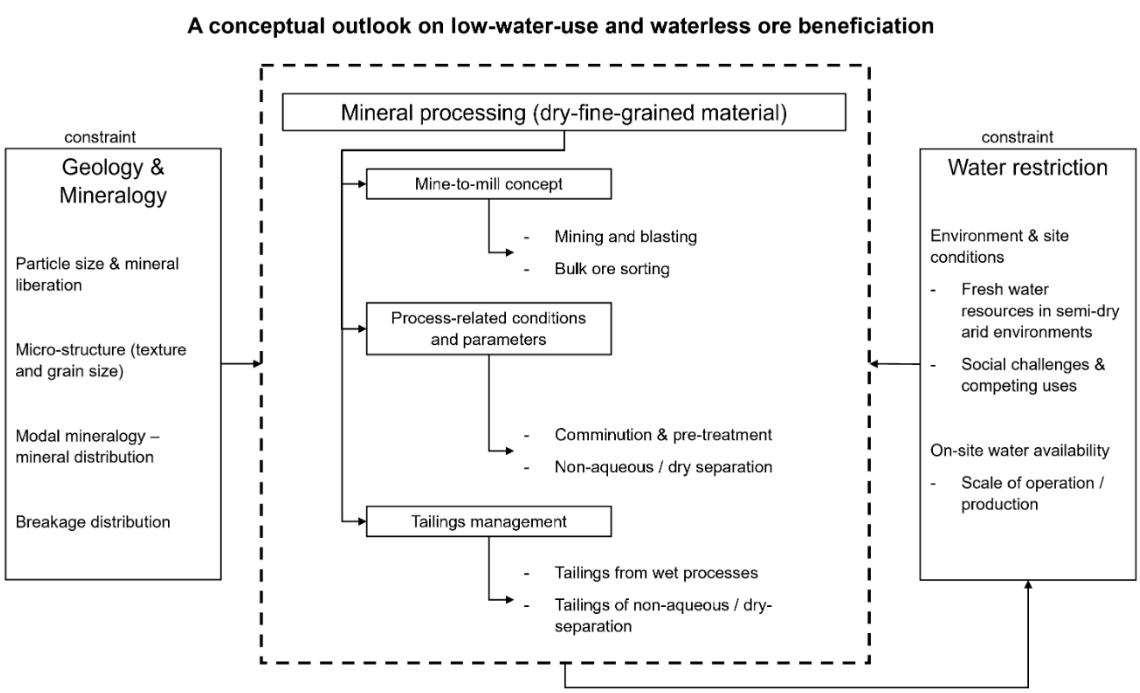

Fig. 1. A conceptual diagram with considerations for selecting mine-to-mill ore beneficiation technologies with low-water-use or waterless focus.

be aware of the presence of deleterious elements and impurities because they can have detrimental impact on the overall profitability of the mining operations. For example, even small amount of impurities can kill an industrial mineral project due to the additional costs their presence bring on. The integration of the value chain mining-milling-metallurgy enables removal of impurities and penalty elements when they are least harmful.

Geometallurgy combines geological and metallurgical information to create a spatially based predictive model for mineral processing plant to be used in production management (Dominy et al 2018, Michaux et al 2019, Lischuk et al 2020). Through a multi-disciplinary approach, it identifies attributes that contribute to the realised value of a resource and enables e.g. ore variability to be factored into the flowsheet. It complements but not replace the traditional approach.

2.2. *Mining and blasting*

A great number of studies on optimum fragmentation, so-called *Mine-to-mill*, have been carried out around the world. Since the 1970 s, it has been recognised that rock fragmentation by blasting affects secondary fragmentation, loading, hauling, crushing and grinding (Zeggeren & Chung 1975). Theoretical analysis indicates that if the energy of the blasting is increased, the overall energy efficiency of size reduction from blasting to grinding can be improved. This is as a result of blasting being more energy-efficient compared to crushing and grinding (Kojovic et al. 1995; McKee 2013; Nielsen & Kristiansen 1996; Zhang & Ouchterlony 2022). In other words, the feasibility of mine-to-mill optimisation is high (Zhang and Luukkanen 2021).

Nielsen and Malvik (1999) investigated the effect of higher powder factor on the microcrack content of two kinds of taconite and one ilmenite samples. They measured the number of each type of microcracks (including small microcracks, boundary microcracks and grain microcracks) by fluorescent microscopic examination, and found that the increase in explosive energy leads to the increase in the density of all types of microcracks. Furthermore, Khademian and Bagherpour (2017) measured the microcrack density of rock fragments coming from blasting by image processing of fluorescent microscopic images and examined the quantity of all kinds of microcracks by some light microscopy techniques. The results showed that different types of explosive have dissimilar influences on rock microcrack network, so that the use of pentolite instead of ANFO increases the microcracks density more than 300 %. It is apparent that such microcracks could help in reducing the energy required for crushing and grinding. Moreover, selective fragmentation along the grain boundaries is expected to produce a narrower particle size distribution (this is considered below in section 2.3.1). If a significant number of such microcracks are intergranular cracks, they could be beneficial to ore recovery in many cases. However, in some cases such as the case of a leaching process or refractory ores where metals are finely disseminated in various mineralogical phases the increasing intergranular cracks may not be beneficial to ore recovery.

2.2.1. *Effect of water on rock fracture by static and dynamic loads*

In metal mines, the ore mass is broken into a wide range of ore fragments including microscale particles by blasting. Unlike mineral processing operations, rock blasting does not need to have water to help ore fragmentation. However, in situ ore masses usually contain a certain amount of water, depending on the ore deposit.

Most rock and ore types are sensitive to the presence of water or moisture under mechanical loads to a certain extent, depending on their type and porosity. Usually, sedimentary rocks and rocks with high porosity are very sensitive to water content. Under static or quasi-static loads, wet rocks usually have lower strengths and fracture toughness (Zhang 2016). For example, the fracture toughness of Johnstone largely decreases with increasing water content (Lim et al. 1994). The specific fracture energy values, the energy required to create one unit area of a crack (J/m^2), of wet Salem limestone and wet Berea sandstone specimens are only about 50 % those of dry Salem limestone and dry Berea sandstone (Hoagland et al. 1973). Under dynamic loading conditions, the effect of water on the strengths and fracture toughness of rock is insignificant. For instance, experiments on Lac du Bonnet granite showed that, under dynamic loading, the effect of water on strength was negligible (Lajtai et al. 1987). However, it has been found that wet grinding in tumbling mills was more efficient than dry grinding (Fuerstenau and Abouzeid 2002).

2.2.2. *Sources of small particles in mining*

In rock blasting, small particles (e.g. < 1 mm) are produced from two sources. One is the crushed zone surrounding the blastholes, where the rock is shattered into small particles by detonation-induced shock waves, and the other is the fractured zone outside the crushed zone. In the fractured zone a propagating crack during blasting may become two new cracks, called bifurcation, or more than two cracks, named crack branching. Measurement and analysis by Reichholf (2013) and Iravani et al. (2020) showed that for iron ore, magnesite and limestone, around 50 % weight of the material < 1 mm was generated within the crushed zone of the blasthole, meaning that the other 50 % of fine particles were not from the crushed zone. Nielsen & Kristiansen (1996) carried out a series of full-scale blasts with different borehole diameters: 76, 89, 102, and 114 mm, and powder factors 0.56, 0.53, 0.56, and 0.60 respectively. After blasting, the muck was crushed to a size less than 70 mm, and then screened through a 32 mm sieve.

The result shows that the weight of particles smaller than 32 mm increases with increasing diameter of blasthole, meaning that the larger holes produce more small particles.

Since the branching cracks were found to increase with increasing loading rate under dynamic loads (Zhang et al. 2000), the weight of small particles outside the crushed zone might increase with increasing loading rate in rock blasting. As the loading rate in the rock is mainly dependent on the detonation pressure (which is related to the diameter of blasthole) as well as rock properties, the weight of small particles will be affected by the diameter of blasthole. In this sense, such small particles from blasting are controllable through blasting design, at least to a certain extent. Small particles can be produced from other mining operations too, such as loading, transportation and crushing at the mine site. In underground mines or open pit mines having ore passes, some small particles might be also produced in the ore passes due to movement of ore/rock fragments, especially when they are very deep. For example, the ore passes were up to 660 m long in the Grasberg open-pit mine (PT Freeport Indonesia, 2022). Results of model blasts using nine granite cylinders show that particles smaller than 50 μm make up 0.07 %–0.21 % of the total weight of each granite cylinder (Zhang et al. 2021). Since the powder factor in the model blasts was only 0.22 to 0.29 kg/m^3, which is much smaller than the powder factor used in real mines, the percentage of the particles smaller than 50 μm in a real mine could be a few times higher than 0.21 %. Thus, it is necessary and important to control the fine-grained material via the operation of rock blasting in a mine.

2.2.3. *Rock cutting, ore blending and optimum fragmentation*

On one hand, rock blasting can efficiently fracture rock; one the other hand it may bring about negative impact on the rock structures nearby and the environment. Accordingly, the methods that do not use explosives become more and more interesting alternative to rock blasting. For instance, rock cutting offers a number of advantages over drill-and-blast mining, and possibly the most significant is that cutting offers the opportunity for continuous operations (Vogt 2016). As a result, the studies on rock cutting have increased in recent years (Zhang and Ouchterlony 2022); hydraulic fracturing has been used in underground mining for preconditioning the orebody (e.g. He et al. 2016); almost half of the worldwide underground coal production has come from longwall mining methods using mechanical shearers, ploughs and continuous miners (Bilgin et al. 2015); diamond wire sawing has been studied and used in some practical tunneling or quarrying projects (Ozcelik et al. 2004; Gustafsson 2010; Ozcelik and Yilmazkaya 2011; Christiansson et al. 2014; Rahimdel and Bagherpour 2018).

In a metal mine the grade and mineral composition of the ore in one part may be different from that in another. To provide a steady and predictable feed to the mineral processing plant, different ores from different parts of the mine can be blended with a proper proportion. This method is called ore blending and it is used in many mines (McKee 2013; Liu et al. 2021). The purpose of ore blending is simply to provide uniform mill feed which aids in improving production efficiency and reducing production cost.

Metso Minerals (2022) introduced an integrated approach, which is similar to the mine to mill approach (Ouchterlony 2003; McKee 2013), in quarries. Two cases of quarry production—a stationary quarry and a mobile quarry—were compared with each other. In the mobile quarry the primary section is mobile, i.e. inpit crushing, which in many cases can yield remarkable benefits because material hauling costs can be reduced considerably. Such an approach focuses on optimum rock fragmentation in the whole size reduction system from drilling and blasting to crushing and grinding. The detail description on optimum fragmentation or mine to mill can be found elsewhere (Ouchterlony 2003; McKee 2013; Zhang 2016; Metso Minerals 2022).

2.3. Bulk ore sorting

Pre-concentration of run-of-mine ore (ROM) to minimise the amount of waste rock in mill feed can be seen as an important aspect of optimising energy efficiency. Removal of waste material from the flow stream prior to energy-intensive grinding has a positive impact on the overall energy efficiency, due to the reduced volume of waste material to be processed by downstream equipment. The grinding mill is often the bottleneck in the grinding circuit and defines the total capacity of the processing plant. Waste rocks occupy space from ore in the grinding mill, thus lowering the mill's ore grinding capacity and mineral concentrator's concentrate production. Moreover, in most cases, waste rock is harder and, consequently, more difficult to grind than the ore which is often found in the weaker areas of the rock. The harder the rock, the longer the grinding time and the lower the mill throughput. Further, hard rock results in overgrinding the ore and higher energy consumption. All this further reduces the capacity of the plant and increases the negative value of the waste in the mill feed. However, in some cases the hard waste rock lumps are used as grinding media in AG and SAG mills.

There are several pre-concentration technologies available, one of them being ore sorting (Lessard et al. 2014; Lessard et al. 2015, Iyakwari et al. 2014; Cutmore et al. 1998, Robben et al 2019). Adoption of sensor-based ore sorting solutions that reduce energy consumption and rationalise water use is becoming of more interest to mining companies especially because improved sensor capabilities and use of artificial intelligence enable more reliable information about the mineral content and facilitate the analysis of the complex data. Bulk ore sorting is based on sorting material combined as bulk mass (Auranen et al. 2020). It enables processing high throughput flows of all particle sizes and is a low-cost, high-value pre-concentration method for all production capacities. Typically, the bulk ore sorting is done after primary crushing on conveyor belt before intermediate stockpiles and further crushing and grinding where ore and waste rock will get mixed (Fig. 2). In case waste rock lumps are used for grinding media in SAG and AG mills the preferred location for bulk ore sorting is on the circulating load conveyor belt which feeds these hard to grind size waste rock lumps to pebble crushers and back to further grinding.

Bulk ore sorting can also be applied in tailings recycling. Any tailings which can be placed and conveyed on belt conveyors can be pre-concentrated in dry or in semi dry form by using on-line XRF analysers and sorting diverter or chute in the end of conveyor.

Other sensor-based sorting methods for sorting individual lumps or particles based on their density, colour, reflectivity, elemental composition, particle shape or other characteristics are limited by capacity i.e. the smaller the particle size, the larger their number and the lower the sorting capacity.

The ore sorting method should be taken into consideration already in the mine exploration and in the mine scoping study and feasibility study phases since the underlying characteristics of the ore grade variation has an impact on mining and processing costs as well as on ore reserves and mine economy. The study can be done fast and economically in connection with other drill core analysis by analyzing the cores by scanning XRF method in short (20 cm) length averages. The amount of ore in the short samples is there after compared with longer core length averages which include small scale dilution, and represent mining block, blast bench or in mining stope dimension. This comparison will give an indication for how much ore is recoverable from the deposit with applying ore sorting method, compared to conventional bulk mining or selective mining methods. The information can further be integrated into mine models (Auranen et al 2020, Auranen et al 2021).

Fig. 2. Pre-concentration solutions for bulk ore sorting (Auranen et al. 2020).

2.4. Comminution and pre-treatment

The comminution operation has a high operating cost due to its high energy consumption and wear of grinding media and liners (Altun et al. 2021). Conventional comminution is very energy intensive and inefficient (Bond 1961, Klein et al 2018). A small fraction of the mill input energy goes into breaking the ore particles while the majority is dissipated in the mill: energy loss through noise, heat and wear can be as high as 99 % (Adewui et al. 2020, Bouchard et al. 2016). Consequently, unnecessary overgrinding is very expensive and moreover, excessive amount of fine material often causes major problems in downstream processing. In the case of dry grinding, the grinding times required are typically longer which means increased energy consumption and increased risk for overgrinding the softer minerals.

Nevertheless, release of fine-grained minerals from low-grade complex ores requires intensive grinding. In general, the efficiency of fine grinding operations can mainly be improved by either enhancing the efficiency of existing grinding equipment and developing new machines, or by improving the grinding behaviour of the ground material (Little et al. 2017). In the former case, technology providers are developing and have developed solutions for more energy-efficient mills (Napier-Munn 2015). The comminution technologies capable of producing microcracks and selective fragmentation along grain boundaries are likely to create fewer fines and are gaining increased interest.

In an attempt to improve the grinding of materials, various pre-treatment techniques have been tested and used (Adewuyi et al. 2021). In downstream processes, physical and/or chemical reactions on mineral surfaces play key roles and to achieve efficient separation between valuable minerals and gangue alteration of surfaces are often needed. For example, for improving the grinding efficiency of fine particles in the lower micron size range using dry grinding processes, so-called grinding aids can be used to reduce the surface energy of the product particles (Prziwara et al 2019; Chipakwe et al. 2020).

2.4.1. Fine crushing and selective fragmentation

In terms of comminution energy consumption, crushing uses less energy than milling. The use of crushing for comminution by improving fine crushing methods can be seen as a more energy efficient solution compared with conventional grinding (Jankovic et al. 2015; Anticoi et al. 2019). For example, rock breaking in roller mills are typically based on compression, which is often seen as more energy efficient than impact breakage and is thus a more convenient choice for fine grinding processes (Lynch 2015). High-pressure grinding roll (HPGR) technology has gained increased acceptance by the mineral processing industry (van de Meer et al. 2010; Guo et al. 2019). HPGR crushes material through interparticle compression and increased liberation levels can be achieved using this breakage mechanism (Ballantyne et al. 2018). HPGR can handle a wide range of particle sizes and is capable of very fine grinding; this method has significantly lower energy consumption compared to conventional tumbling mills.

Hugger (Fig. 3) is a newly patented industrial crushing and classification device, developed by the University of Oulu (Kuopanportti et al. 2020). The main components of Hugger are two lamella conveyors, installed vertically in a double converging position. Crushing is based on uniaxial slow compression and, during the operation, individual particles are sequentially broken down by size between press plates. In comminution, the loading shape is set to converge in both the horizontal and vertical directions into an exit gap of constant width. For classification, the particles smaller than the gap size fall out of the loading space. Preliminary tests have indicated that, compared to conventional crushing, this method produces more crystalline and cleaner surfaces, higher surface area and higher density of microcracks with the minimum amount of energy. Microcracks that occur along mineral boundaries assist in achieving preferential liberation. Due to the operating principle, formation of fine material is minimised. Hugger has been successfully used for breaking various type of primary and secondary raw materials. Currently the machine is available in pilot scale.

Fig. 3. Hugger crusher (Kuopanportti et al. 2020).

2.4.2. Vertical roller mill (VRM)

Another promising comminution apparatus under research is the vertical roller mill. VRḾs working principle revolves around grinding the feed material between a rotating table and several grinding rollers that are hydraulically pressed onto the table. As the table rotates, the ore bed moves under the grinding rolls and is fractured by the applied pressure and friction as it is compacted between the rolls and the table. The ground material is then ejected from the mill by air flows into a rotary classifier that is placed in the immediate vicinity above the milling space.

The main benefits of the VRM compared to the traditional tumbling mills are the reduced energy consumption (Flieger et al. 2015; Rashmi Cement Limited 2015; Genc 2016) and improved mineral liberation due to the grain boundary specific particle breakage profile (Reichert et al. 2015). Cons are mostly related to the excessive vibrations typically caused by too fast rotation of the grinding table. Normally water spray is used to stabilize the fine particle mineral bed but the VRM can be operated in completely dry conditions also. (Pareek & Sankhla 2021; Pohl et al. 2012).

VRM has been widely researched in processing of cement (Ito et al. 1997; Jorgensen 2005; Wang et al. 2009, Ghalandari et al. 2021)), coal (Tontu 2020), iron ore (Reichert et al. 2015), zinc ore (van Drunick et al. 2010), copper ore (Viljoen et al. 2001; Altun et al. 2015), gold (Erkan et al. 2012; Altun et al. 2017), nickel ore (Viljoen et al. 2001), etc., and it has been commissioned in industrial scale in several cement and coal power plant operations around the world, but is still gaining traction in the realm of hard rock mineral processing.

2.4.3. Dry grinding

As stated above, dry grinding uses more energy than wet grinding. To achieve targeted particle size distribution takes longer with dry grinding and, moreover, a high agglomeration rate of particles using dry grinding results in coarser grinding products. Dry grinding processes and their impact on the results of downstream processing, such as flotation, have been investigated for several different types of minerals, with both advantages and disadvantages being noted. A study (Palm et al. 2010) showed that dry grinding caused the formation of a passivating layer of ions on the sulphide mineral surfaces and increased the amount of very fine material, both of which were expected to cause a negative impact on the flotation of sphalerite. In addition, dry grinding prior to flotation has been shown to have a negative impact on the grade and recovery of pyrophyllite as a function of grinding time, due to the altered surface structures during grinding, although the grade and recovery increase with very long grinding times (Erdemoğlu & Sarikaya 2002). On the other hand, dry grinding has been reported to improve the flotation kinetics of sulphide minerals (Feng and Aldrich 1999). This has been attributed to rougher surface topology of the minerals produced by dry grinding, thus increasing the adsorption sites on the particle surfaces and producing a positive impact on the attachment of collectors (Feng and Aldrich 2000). Compared to wet grinding, reduced wear of grinding media and consequently reduced negative impact from galvanic interactions have been reported after dry grinding (Peltoniemi et al.2020).

To be able to recover fine-grained commodities from complex ores, efficient solutions for liberating them are required. When targeting fine and ultrafine particle sizes, energy usage is naturally high with only a small percentage, used for grinding, efficiently utilised for the generation of fresh surfaces. Various types of stirred media mills for producing fine particles have been introduced (Mineral Processing Design and Operations 2016). Stirred media mills can operate both wet and dry operations, with wet grinding clearly more energy efficient. A recent study by Altun et al. (2020) evaluated the applicability of the dry stirred media milling technology for different streams in conventional cement grinding processes, to improve energy efficiency. The results indicated that the production rates increased, leading to reduced energy consumption. It has been reported (Prziwara et al. 2021) that the efficiency of dry stirred media mills can be significantly improved by the use of additives, so called *grinding aids* (section 2.3.4).

2.4.4. Air classification

Part of the energy consumption for dry grinding is related to the classification stage. In industries producing fine powders, the classification process is considered to be one of the most crucial operations. It is used to ensure the particle size of powder products meets the client's requirements.

Air classifiers are used to separate and recover fine and coarse materials in various industrial applications and are particularly used by the cement industry (Altun et al. 2016). In an air classifier, particles of varying size, shape and density are acted upon by fluid drag, gravity and buoyancy forces. Both static and dynamic types of classifiers are available. In static air classifiers there are no moving parts and the adjustment of the cut size is completely dependent on the airflow rate. In dynamic classifiers there is a rotating table or rotor cage enhancing the separation efficiency (Lynch 2015).The cut size is an important factor with which to evaluate the performance of an air classifier. Various operating parameters impact on the separation efficiency and cut size. Energy consumption of air classifiers in fine-grinding classification processes is high which emphasises the need to optimise the production of fines in the preceding operations.

Air classifiers can be built sealed into the processing equipment, such as mills and separators, so that dust hazards are minimised (Metso 2018). Apart from physically moving the ore, they can simultaneously separate particles based on size, and dry the ore, making the process more efficient. Separation of the fine fractions during the normal planned transportation could optimise the dry separation processes that traditionally struggle with fine particles, or otherwise work more efficiently with narrower size ranges (e.g. gravity separation) A set-up such as this could be used to funnel certain particle sizes to individual separators that have been optimised to treat particles in a certain size range, increasing the overall separation efficiency. Various cyclonic separators and air classifiers have been used in numerous applications to separate a wide range of particle sizes (10-1700 microns), and some are able to handle relatively coarse ore streams (>5 mm) (Metso 2022a).

2.4.5. Pre-treatment

The use of pre-treatment methods to pre-weaken ores in order to reduce energy consumption of comminution has been studied by several researchers (Prziwara et al. 2019 and 2020; Chipakwe et al. 2020). In general, the main objective of using these methods is to make the grinding operation easier by creating intergranular cracks and thus reduce the grinding energy required. In addition to the selective fragmentation described above, other pre-treatment methods that have been studied include thermal, microwave (MW), chemical additives (grinding aids), electric, magnetic, ultrasound, radio frequency and bio-milling (Adewuyi et al. 2021). Apart from size reduction, pre-treatment techniques can be used to modify mineral surfaces to make them more susceptible to downstream processing. The principles of operation vary between different methods, for example, a combination of thermal treatments can be used to magnetise iron that contains minerals selectively (Yu et al. 2019). The use of magnetic materials to coat mineral surfaces selectively has been reported to enhance the magnetic properties of the minerals (Yuan et al. 2020).

2.4.6. Grinding aids

The use of chemical additives is one of the most common ways of pretreating ore before grinding (Chipakwe et al. 2020; Prziwara et al. 2019). The energy required for dry grinding can be reduced using surface active compounds such as grinding aids, which are widely used in industrial dry fine grinding processes, such as by the cement sector. The advantages of using grinding aids are reported to be reduced energy consumption, increased production capacity and the potential to produce finer particles from grinding (Sverak et al. 2013). Grinding aids are typically active on ore surfaces causing local stresses and thus allow fragmentation at the grain boundaries during grinding. An advantage of such grinding aids is that they are not typically limited to specific mill types, meaning they have applications in a variety of grinding operations.

Although the benefits of using grinding aids have been shown in various experimental studies, a comprehensive understanding of their impact has not been fully realised. Prziwara et al. (2019) studied the effect of different grinding aids when grinding selected solid materials. Based on the study, the surface energy of the product particles significantly decreased when using grinding aids from different substance classes. It was noted that the resulting surface energies correlated with powder properties such as flowability of the ground material which relates to the solid-specific behaviour of grinding aids.

2.4.7. Microwave

Several reports have indicated that microwave-assisted grinding can improve the grindability of various minerals (Adewuyi et al. 2021, Elmahdy et al. 2016, Bobicki et al. 2018) The research into its effect on the release of South-African carbonate ore showed that microwaves can improve release of minerals (Scott et al. 2008). It was suggested that intergranular breakage of ores along grain boundaries was achieved with microwave pre-treatment as a result of the differences in microwave absorbance between different minerals, causing them to expand at different rates when heated and crack along the boundaries. Microwave radiation has typically been studied in connection with mechanical comminution but also as the sole method of comminution. From an energy efficiency point of view, the use of microwaves is highly dependent on the energy input required to break the material: if the microwave energy required to effect comminution in a particular application is relatively high, any total energy saving may be reduced or zero. In addition to its potential use as grinding aid, microwave irradiation affects the magnetic properties of certain iron-bearing minerals which facilitates magnetic separation of the minerals (Elmahdy et al. 2016).

2.4.8. Gas dispersion

The dispersal of gases or chemicals in gaseous form in the mineral processing field has not been extensively studied but could potentially offer more efficient conditions for chemical dispersion compared to mixed slurries. However, a gas-based system with potentially hazardous and toxic chemicals would introduce safety risks and complexity to the process in terms of gas-proof sealing of the equipment and overall handling of chemicals. Gaseous conditioning is not one of the most pressing challenges to solve to enable the more widespread adoption of dry processing methods, as most of the established methods operate based on properties such as density, magnetism and conductivity rather than surface chemistry. However, gaseous conditioning in separate gas-proof tanks and control of the chemical atmosphere during grinding might have some other applications, for example, in flotation. It has been reported that the addition of carbon dioxide into the grinding mills prior to flotation of low sulphur PGE ores led to improved recovery of platinum and palladium (Maksimainen et al. 2010).

2.4.9. Drying

Comprehensive drying of feed is required before certain dry separation methods such as electrostatic separation (Lindley et al. 1997), but the amount of energy needed for drying feed with a low moisture content is much smaller compared to the dewatering of the concentrates and all the additional steps needed in water management. When drying of feed is required, it is of utmost importance to optimise the pre-concentration methods such as sorting to minimise the feedstock ending up in the process and requiring drying. Air classifiers may also prove beneficial with regard to drying as the air flows transporting the ore might remove some of the moisture during transportation and separation (Metso:Outotec 2022b).

2.5. Available technologies for dry separation

Dry beneficiation technologies separate minerals from waste based on differences in physical properties such as particle size, specific gravity (gravity separation), magnetic properties (magnetic separation) and electrostatic properties (electrostatic separation). When the difference in one of these properties between valuable and gangue mineral is large enough, separation is often straightforward. However, efficient separation of fine particles starts to become challenging as the particle size decreases below 100 μm because of the changing balance between gravitational, magnetic and electrostatic forces in relation to van der Waals and interparticle attraction forces. This shift causes small particles to form agglomerations and stick to larger particles, making separation difficult, or in most cases even impossible with traditional methods (Wills & Finch 2016).

The difficulties outlined here mean that it is important to carry out mining and comminution such that as few fines and ultrafines as possible are produced, thus facilitating optimal conditions for dry separation methods. As described above, this can be achieved by optimising blasting, establishing an efficient ore sorting system, using suitable pre-treatment methods and choosing comminution methods that produce fewer fines.

The most common dry separation methods and their applicability in regard to fine particles are described below.

2.5.1. Gravity separation

Gravity separation methods are based on exploiting the differences in specific gravities of minerals. For clean separation, particle size distribution should be as narrow as possible for the best possible outcome. This puts an increased emphasis on efficient screening and classification when feedstocks are prepared for gravity separation operations.

The working principle with most gravity-based methods is that the feedstock is fluidised or made to flow by vibrating, shaking, sliding or pneumatically using air, causing the mineral particles to stratify or group into different layers or trajectories as a result of their density. Thus, they behave more like a fluid, which enables them to be separated from each other. Most dry gravity-based methods such as air fluidised beds, shaking tables and dry spirals are often employed to process coarse particles with sizes 1–15 + mm only, but some can extend their operation ranges down to 100 μm with varying results. There is also research being carried out on utilising the principles of traditional wet methods, such as the Knelson concentrator for dry processing (Kökkılıç et al. 2015), as well as inventing completely novel separators such as the fluidised sink-hole separator (Kumar et al. 2018; Kumar et al. 2020).

For gravity separation applications, as particle size decreases (<100 μm), the effect of gravity relative to other forces, such as cohesion and van der Waals forces, becomes less pronounced and efficiency decreases. There are several methods utilising centrifugal forces and cyclonic separation for powder processing of fine/ultrafine particles – 10 μm up to the nm scale – that can help in the handling of fine particles (Fu et al. 2016; Hiraiwa et al. 2013; Konrath et al. 2014; Metso 2022a). Various rotational effects generated by air flows and different geometries in the separator chambers are used to drive the separation process in these types of separators, and they appear to be the most promising gravity separation methods for fine particles. Common applications by the mineral processing industry are found in operations where the density difference between valuables and gangue is significant, for example, gold, lead, iron and coal production, but examples can also be found in copper, silver, fluorite, tungsten, chromite, garnet and sand processing

2.5.2. Magnetic separation

Magnetic separation uses magnets and magnetic fields to separate minerals. Separation selectivity is based on differences in magnetic properties of minerals that are either inherent in certain minerals or can be induced with various pre-treatment methods (Faris et al. 2019; Koleini & Barani 2012). Magnetic separation can be used with ferromagnetic minerals but is more difficult with weakly magnetic paramagnetic and diamagnetic minerals. The success of the separation is governed by competition between magnetic, gravitational and inertial forces, and interparticle attractive and repulsive forces, which are mainly determined by the particle size, density, magnetic properties of minerals and the intensity or gradient of the applied magnetic field.

Magnetic separation is often carried out as a wet process but there are numerous examples of dry magnetic separation in the mineral processing industry, especially in iron ore and coal beneficiation (Andre et al. 2019; Bunting 2022; Miceli et al. 2017; Tripathy et al. 2017; Zong et al. 2018). Other example applications include the removal of iron minerals (mostly magnetite) from ores, silica sands, feldspar and other non-metallic industrial minerals, processing of granulated slag, upgrading ilmenite, processing beach sands, and in recycling applications such as removing fine iron material from recycled glass.

There are a number of magnetic separators available such as the induced magnetic roll, rare earth magnetic roll, magnetic disc separator and drum separators. The working principle behind most of them is that magnetised surfaces, such as rolls or plates, attract magnetic minerals directly from the bulk stream, or that a change in trajectory of magnetic minerals in a flowing or falling stream is induced using a converging magnetic field which funnels minerals into separate collection areas. Ferromagnetic and paramagnetic minerals move in the direction of increasing field strength while diamagnetic minerals are weakly repelled.

Fine particles tend to cause problems with selectivity as they can become trapped between coarser magnetic particles or adhere to the surfaces of coarse particles. The typical magnetic separation operating range is around 75 μm to 15 mm but there are several available capable of handling very fine particles down to 45 μm (Bunting 2022). Processing of fines has been attempted using magnetic separation methods in a centrifugal field. This enhances the separation efficiency especially with paramagnetic minerals such as ilmenite and introduces the effect of stronger gravity separation component to the equation (Lindner et al. 2014). The increase in efficiency is caused by inducing movement of fine particles in the mineral bed which decreases entrapment and facilitates particles to move on or near to the magnetic surface.

2.5.3. Electrostatic separation

Electrostatic separation of minerals exploits the differences in minerals' electrical properties such as conductivity, contact potential and dielectric constant. Electrostatic charges are used to attract or repel charged material, for example, by attracting conducting material to an oppositely charged surface, by causing charged particles to jump out of similarly charged or earthed surfaces, or by changing the trajectory of different falling mineral particles in an electric field, dependent on their conductivity.

Minerals can be divided into conductors, semiconductors and insulators, based on how easily electrons move in the material. Metals, sulphides, heavy metal oxides and graphite are typical conductors/semiconductors while most other minerals, such as silicates, are insulators. When mineral particles are placed into an external electrostatic field, electrons start to reposition themselves, dependent on the field polarity and strength. Depending on the minerals' electrostatic properties, the electrons may become charged and gain an electric dipole. Other options for generating charges are rubbing minerals against surfaces or other minerals with differing dielectric constants (tribocharging), or by bombarding them with charged ions or radiation (ion/electron/UV bombardment).

As with the other dry methods, selective separation of fine particles is challenging due to other forces becoming more prominent relative to the electrostatic forces as particle size decreases. However, electrostatic separators are probably-one of the most effective methods of dry fine particle processing in optimal conditions, with some traditional separators having working ranges down to 40 μm (Mineral Technologies 2022). Some new machines tested in the laboratory have been able to work on particles as small as 10 μm (Adachi et al. 2017; Bittner et al. 2014).

There are, however, strict requirements for feed moisture content, which must be essentially zero since the water on the mineral surfaces makes all particles conductive and therefore disrupts the process. This fact alone places extra demands on designing a working process around electrostatic separation and pre-treatment of the feedstock. Additionally, many of the separators based on electric phenomena require direct contact with the particles and the separator surface, which restricts capacity, especially when processing fine particles.

The main categories of electrostatic separators exploit drastically different phenomena, namely conductive charging, induction, tribocharging and radiation charging, and they should be considered separately. There are also some novel ideas being developed such as using travelling waves (Adachi et al. 2017; Kawamoto et al. 2011) but the work is still ongoing.

The tribocharging phenomena is somewhat different in its nature compared to conductivity, and might enable separation between a wide range of different minerals compared to separating conductors from insulators. Another difference is that the charge generation is a surface phenomenon which requires direct contact with the different materials and surfaces for all particles, which might pose challenges in regard to capacity and processing of fine particles. Tribocharging separators are being investigated extensively (Chen & Honaker 2015; He et al. 2019; He et al. 2020; Wang et al. 2014; Xing et al. 2018) and several novel ideas using the phenomenon have been developed. Some are claimed to be able to handle even ultrafine particles (<1 μm) (Bittner et al. 2014).

In some cases, various customized functionalized reagents can be used to pretreat the ore to selectively increase the conducting or non-conducting properties of minerals, improving the separation efficiency. The chemical treatment is performed in wet conditions before drying the feed and can be utilized as an enhancer in any electrostatic separation process where conducting and non-conducting minerals are present. Examples include rutile-zircon separation (Ravishankar & Kolla, 2009), mineral sands, ilmenite-staurolite, ilmenite-monazite, zircon-leucoxene, iron ore-silicate, hard rock ilmenite, hard rock rutile, metal recycling, kyanite-zircon, cromite-garnet, celestite-gypsum, etc. (Ravishankar et al. 2019).

Other methods include doping of semi-conductors with different compounds to promote their conductivity or non-conductivity properties (Kelly & Spottiswood 1989). Likewise in the flotation process, rendering minerals selectively hydrophobic can modify their conducting properties for the electrostatic separation. As the treated ore mass is put into a humid atmosphere, hydrophobic particles will stay dry and attain their properties while hydrophilic particles will gain a conducting water layer, which renders them conductive. Similarly, hydrophilicity can be induced with various chemicals to render naturally hydrophobic non-conducting particles conductive (Kelly & Spottiswood 1989). (Lindley & Rowson 1996).

Conditioning minerals with HF gas and other various acidic gases have been shown to promote conductive film formation, which has been used to induce conductivity in silicate minerals. The above method has been utilized especially in selective separation of quartz from aluminosilicate minerals as quartz is not amenable to conductive fluoride film formation. (Fraas & Ralston 1940; Lindley & Rowson 1996).

2.5.4. Solvometallurgy

Solvometallurgy – a complement to hydrometallurgy and pyrometallurgy – is described as an emerging technology for metal processing where little or no water is involved in the process. Solvometallurgy is essentially traditional acid leaching using organic solvents instead of water (Binnemans et al. 2017, Peeters et al. 2020). Two immiscible non-aqueous liquids (organic solvents, ionic liquids, deep eutectic solvents and inorganic solvents) form a solution in which the feedstock is processed (Binnemans et al. 2017). With the aid of extractants, metal ions are selectively made soluble from the feedstock, after which they spread with certain affinities based on their solubility to the immiscible solvents in the solution, and are separated using solvent extraction after the leaching has finished. Dissolved metals are then recovered from the solvents by precipitation or electrolysis. The main properties needed from the solvents are stability, recyclability, low price, low environmental impact, safety, low toxicity, and biodegradability.

One of the driving factors in the adoption of solvometallurgical processes is the minimisation of water consumption. The environmental impact and the safety of organic solvents need to be considered but reduction in industrial water usage has several benefits: i) freed-up water from the metallurgical processing can now be used elsewhere in the society, ii) no generation of wastewater that could be discharged into the environment, but instead, degraded contaminated organic solvents are produced that can be burned and the heat recovered, and iii) possibly easier to be allowed to use because of greater social acceptability from local inhabitants and governments, as local water resources are not depleted. Closed loop processes are usually also considered as being more acceptable. However, it should be emphasised that the recyclability and the ability to reuse degraded solvent liquids needs to be improved before they can be considered an environmentally friendly option to using water.

It has also been reported that solvometallurgy has better leaching selectivity with some ore types compared to the traditional acid leaching process. Better selectivity might enable the leaching of even lower grade feedstocks such as tailings, currently uneconomical ores etc. It may also make purification of liquids potentially easier due to a less diverse ionic variability in the solution (less gangue leached). Increased selectivity also reduces chemical consumption as extractants have higher affinities for the desired minerals and are not wasted on extracting gangue. (Binnemans et al. 2017). Overall, leaching methods are well suited to fine particle processing as reducing particle size increases the leaching kinetics due to increasing surface area.

A summary of the key features of available technologies for dry separation is provided in Table 1.

3. Tailings management

3.1. Tailings from conventional processes

Dewatered tailings, such as paste tailings and dry stack tailings

Table 1
Anticipated key facts and examples of a waterless ore beneficiation.

KEY FACTS				
Blasting	**Crushing & grinding & comminution**	**Transport & Sorting**	**Beneficiation & Separation**	**Tailings management**
Selective fragmentation and intergranular microcracks created by blasting can be beneficial to ore recovery incl. energy efficiency in crushing and grinding. Dry blasting however may consume more energy than blasting wet rocks. (Zhang 2016) (Lim et al. 1994) (Hoagland et al. 1973)	Dry grinding is less efficient than wet grinding (Fuerstenau and Abouzeid 2002) as it may require more time and therefore more energy. Prolonged crushing and grinding times can overgrind soft minerals and create more fines. Complex and disseminated ores require more grinding for mineral liberation. Dry grinding can reduce wear of grinding media and reduce the effect of galvanic interactions.	Pre-concentration of run-of-mine (e.g., ore sorting) reduce waste and is key to increase productivity and rationalise water use.Ore sorting based on particle characteristics (e.g., density, colour, reflectivity, elemental composition, particle shape) . Sorting capacity is limited when particle size gets finer. Dust challenges.	Separation based on differences in physical properties in valuables and gangue.Separation is challenging below the 100 µm range in particle size (Wills & Finch 2016). Efficiency of dry separation methods is adversely impacted by the presence of fine and ultrafine particles.	Handling and disposal of tailings is driven by the long-term physical and chemical stability criteria. The design criteria for the stability of tailings can influence the decisions made concerning prior stages in the value chain. Tailings from waterless separation methods may undergo further conventional concentration and dewatering processes.
EXAMPLES/REFERENCES				
Dry separation method	**Ore / mineral type**	**Crushing & grinding**	**Transport, Sorting & Separation**	**Tailings management**
Gravity separation	Where valuables and gangue have significant differences in properties, e.g., copper, silver, fluorite, tungsten, chromite, garnet, sand processing.	Operating range with coarse particles between 1 and 15 mm. With fine-grained ore, between 15 and 500 µm and as low as 5 µm (Andò, 2020). Efficiency decreases with fine/ultrafine particles < 100 µm.	Fluidised (vibrating, shaking, sliding, airflow). With fine particles, dust issues.	Tailings are mostly considered for further processing, e.g., leaching or flotation. It follows a conventional dewatering process.
Magnetic separation	Ferromagnetic minerals. Weak with paramagnetic and diamagnetic minerals Iron ore, coal. Processing iron from ilmenite, silica sands, slag, recycling applications.Cassiterite ore (tin)	Operating range is between 75 µm and 15 mm for particle size. Separation of very fine particles down to 45 µm is possible (Bunting 2022)	Transport: Magnetic rollers, moving belts. Sorting & Separation: Magnetic separators and magnetised surfaces. Often carried out in a wet process.	Considered for further processing, e.g., flotation (Schreiber et al., 2021). After conventional dewatering, low rate of settling & consolidation.
Electrostatic separation	Rutile-zircon (Ravishankar & Kolla, 2009), mineral sands, ilmenite-staurolite, ilmenite-monazite, zircon-leucoxene, iron ore-silicate, hard rock ilmenite, hard rock rutile, metal recycling, kyanite-zircon, cromite-garnet, celestite-gypsum, etc. (Ravishankar et al. 2019) Iron ore fine tailings.	Operating range for particle size can be as low as 10–40 µm (Mineral Technologies 2022; Adachi et al. 2017; Bittner et al. 2014).	In mineral sands, often complemented with magnetic separation. Dust issues during transport.	Tailings are considered for further processing (wet magnetic separation) or reject considered as middling subproducts.
Solvometallurgy	Rare earth minerals Complex and disseminated ores Low grade feedstocks, e.g., uneconomical ores, tailings.	Valuables are ground fine to dissolve valuables. More intense with more fines. Dust issues but mostly a low-water wet process.	Fluidised or hydraulically transported. Separation by solvent extraction, precipitation or electrolysis.	Conventional dewatering process. Low rate of settling & consolidation with fine particles in excess.

derive from wet processes but they are more aligned with water efficient treatment and processing (Fig. 4). There are benefits to dry stacking compared with wet tailings, as it can optimise land use, reduce groundwater contamination through seepage, and minimise the risks of dam failure. Handling dewatered tailings is more manageable compared to slurry deposition, but it poses other challenges such as excessive fines and dust management. Also, dewatering of thickened and paste tailings increases costs as the throughput is higher. For instance, filtered tailings are considered not economically viable at throughputs above 50–100 k tpd.

Fig. 4 below shows the range of applications for the dewatering of tailings (MEND, 2017).

An important consideration for managing tailings concerns its final disposal. The mechanical strength of tailings and therefore their physical stability depends on the moisture content for optimum compaction. This means that, for dry tailings resulting from a waterless process, the fine tailings will undergo wetting and compaction. In conventional tailings, the moisture content for optimum compaction can be 12–18 % v/v. In clays (<2 µm), the moisture content for optimal compaction is higher (12–24 % for inorganic clay, and 19–36 % for highly plastic inorganic clay) but it is not advisable to use clays, or any other fine material for that matter, in structural zones as they are prone to volumetric changes. This raises the question of how fine the ore needs to be ground and whether the benefits of value recovery can offset the liabilities of future tailings management.

The presence of fine particles in tailings is also a challenge for dewatering processes. For instance, their low settling rates require larger than normal equipment such as thickeners, filters, or centrifuges. In dry stacking operations, fine particles and specially clay particles are a major problem, negatively affecting the efficiency of filter presses with respect to cycle time, air blow, wash cycles and the like, in addition to the durability of filter cloths. Another issue is dust which, in dry environments, can only be controlled by wetting the material.

It is also believed that dry stacking of tailings may be pushing the performance of filters to their limits without considering the position of the tailings in the value chain. Tailings at the disposal site (for structural zones) should have a moisture content suitable for optimum compaction, something that is critical to increase the strength of the tailings and to ensure geotechnical stability. This moisture content should be determined by the operating conditions of the filtering system, and can

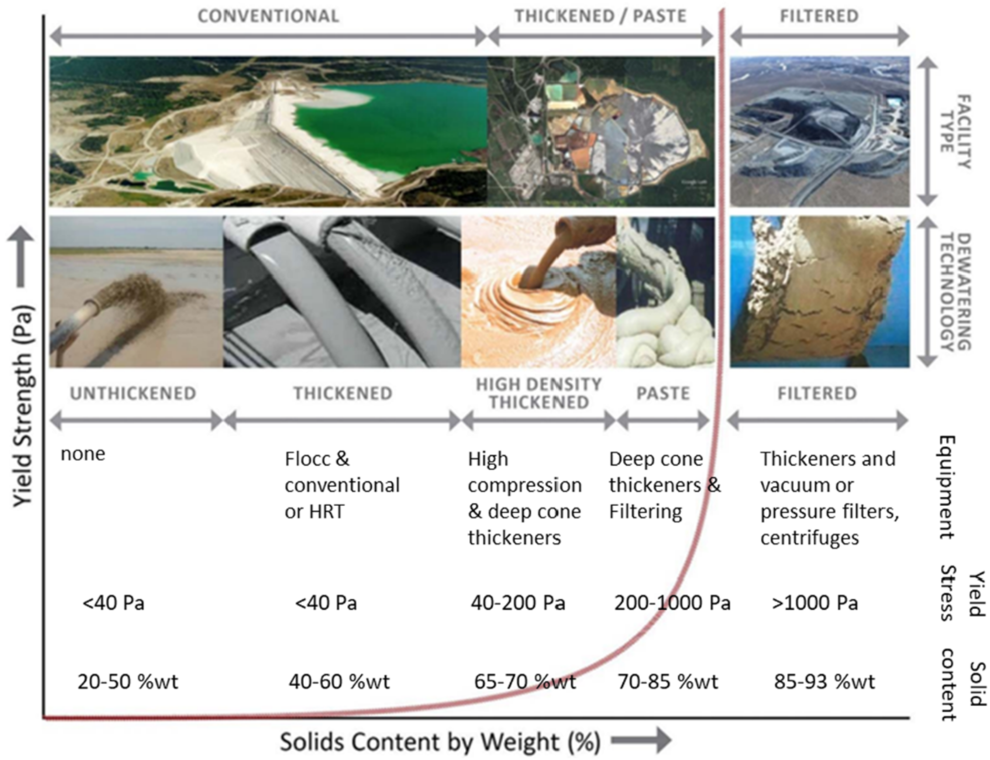

Fig. 4. Range of application for dewatering of tailings. Source: After MEND 2017.

range from 12 % up to 30 % v/v depending on the environment, deposition, and geometry of the stack (Crystal et al. 2018). Dry stacking of tailings does not imply dry tailings, because pressure filters or centrifuges cannot remove all the water from the tailings. However, this may be beneficial because the moisture required by the tailings material at the final stack can be managed.

An illustration that clearly shows the benefits and challenges of the various types of tailings deposition is shown in the Fig. 5 (below) (Davies & Rice, 2001; LPSDP, 2016).

3.2. Tailings from non-aqueous/ dry separation

The characteristics of the tailings material will be the result of the treatment and processing outputs in the value chain. The particle size reduction will follow the requirements for mineral liberation and the selected concentration method. As such, the particle size distribution of the tailings material will be determined by the preceding stages in the value chain. While tailings management cannot dictate the specifications for particle size of tailings or mineralogy, the design criteria for the

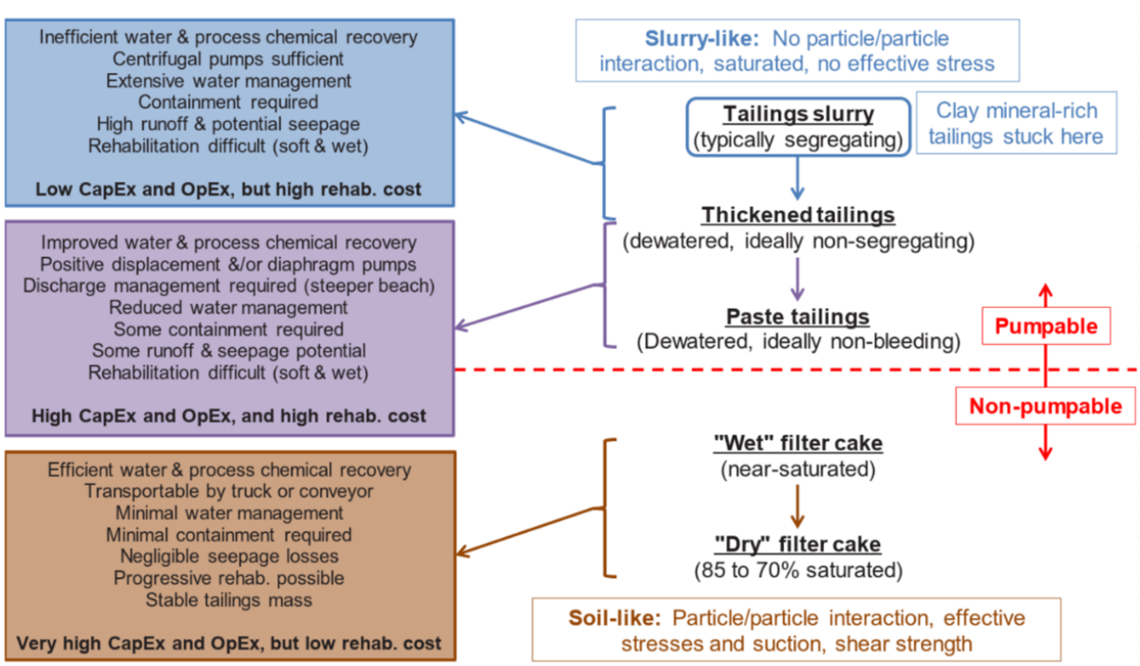

Fig. 5. Benefits and challenges of tailings dewatering technologies. Source: (Davies & Rice, 2001; LPSDP, 2016).

stability of tailings can influence the decisions made concerning prior stages in the value chain. For instance, in dry stacking, these criteria are associated with the clay content of the tailings, moisture content for optimum compaction, environment, deposition strategy and the geometry of the dry stacking among others.

Gravity separation is based on distinctive mineral properties such as grain size and density characteristics of heavy minerals. The conventional focus on the sand fraction covers a narrow grain size window of the heavy mineral spectrum which, in terms of tailings grain size, it is not difficult to handle. By expanding gravimetric separation to fine-grained ore and to sediment systems (loess deposits, shallow to deep marine muds), the grain size of the tailings can be still in the medium silt to medium sand 15–500 μm range, and with some fractions as low as 5 μm (Andò, 2020). In the case of magnetic separation, such as for iron minerals, there are several crushing and grinding stages with the tailings passing through a froth flotation process (Schreiber et al., 2021). For instance, in high-grade magnetite ore, the grain size of the gangue minerals (tailings) after magnetic separation is in the 45–75 μm range (Baawuah et al. 2020b). The relationship between grain size and mineral liberation will define whether the tailings from physical separation methods (e.g., gravity, magnetic or electrostatic) require a further concentration process such as froth flotation, and from that point, the processing can use dewatering technology.

4. Summary

Sustainable production of primary raw materials required by the green shift is not possible without drastic changes in operations. Despite the increasing recycling rates, demand for commodities require increasing quantities of newly mined ores. Conventional mineral processing methods are highly water-intensive and, consequently, more mining means more water is required. This emphasises the importance of finding alternatives to the water-intensive grinding and separation methods currently in use.

Low-grade complex ores require energy-efficient solutions for liberating fine-grained commodities while, at the same time, it is a challenge to deal with the increased amount of fine-grained waste material. Efficient handling in the rock breakage chain from mine to mill, from blasting to grinding, requires a comprehensive view of the rock type and characteristics which highlights the need for close collaborations between mine geologist, mining engineers and process engineers.

The shift of mineral processing operations from wet to dry or waterless media is key to mitigating the water stress of mining. Dry separation technologies, capable of efficient separation of wanted minerals from gangue, are relatively rare and their efficacy is highly dependent on the materials to be separated. Application of pre-concentration methods to remove barren waste prior to grinding, developing of cost-efficient and energy-efficient methods for comminution, use of mechanical or chemical pre-treatment methods for modifying the mineral surfaces and replacing water by solvents in leaching are good tools to use when considering the change from wet to waterless processing. Nevertheless, considerably more multidisciplinary research, along with new methods and holistic, innovative solutions are required to enable such a change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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