Plugging mechanisms and plugging reduction techniques in heap leaching operations: a review

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Abstract

Plugging of pore spaces is the most significant contributor to ponding, decrease in the mineral resource recoveries and stability problems in heap leaching operations as ore permeability is reduced. Consequently, the identification of different plugging mechanisms is very important for optimisation of heap leaching processes. This paper reviews various pore spaces plugging mechanisms, including ore heap compaction, migration of fine particles, presence of large fractions of clays in ores, agglomerate destruction under acid effect and dissolution-precipitation processes. Proactive plugging reduction techniques including ore placement, ore agglomeration, heap aeration and lixiviant application techniques are also explained as means to prevent pore spaces plugging during heap leaching operations. The findings of this paper can be useful in guiding laboratory and industrial heap leaching operations.

Key words: heap leaching, plugging mechanisms, pore spaces, permeability, recovery

1. Introduction

Heap leaching is well known as one of the most cost-effective hydrometallurgical techniques for extracting metals (copper, gold, nickel, uranium…) from low grade ores. Heap leaching operations typically consist in sprinkling a leaching solution over an ore heap placed on a lined pad; and recovering the pregnant leach solution (PLS) at the bottom using well designed piping system schemes. The ore heap should have a good permeability to allow the leach solution and air to move freely through it and therefore to promote an adequate reagent-ore contact.

The numerous foot and truck traffic manoeuvres on the top of heaps when processing finely crushed ores, especially when agglomerated, generally lead to a consolidation or compaction of ore heaps. This will result in the obstruction of pore spaces referred to as plugging mechanism. This phenomenon can decrease seriously the ore heap permeability. This will lead obviously to ponding, ore heap stability problems and to a decrease in mineral resource recoveries during heap leaching operations. Plugging of pore spaces can also be aggravated by ore agglomerate destruction under the effect of acid aqueous leach solution, dissolution-precipitation processes driven by local variations of fluid saturation and segregation of coarse and fine particles during ore heap construction and heap leaching operations. The presence of fine particles (particles smaller than 75 µm size particles) can also enhance the plugging mechanism. Fine particles can easily migrate into larger pore spaces and impede a proper conduct of heap leaching operation. The success of heap leaching operations generally depends on the correct execution of the following standpoints (Muhtadi, 1988): ore pre-treatment method (crushing and agglomeration), placement method of ore on the leach pad (gradation, packing and orientation of the ore heap) and leach solution sprinkling technique. This paper reviews and discusses practices commonly used in the heap leaching industry in order to enhance the permeability of ore heaps, thereby optimising the recovery of mineral resources.

2. Flows through ore heaps

Ore heap permeability is the one of most important parameter to consider when conducting heap leaching operations (Milczarek *et al.*, 2012). Insufficient heap permeability can lead to the failure of heap leaching projects. Poor permeability means slow solution flow and results in uneconomic leach cycle times. In addition to this, recovery is reduced due to incomplete wetting of the heap. Low permeability also limits air ingress, a necessity for bacterial leaching operations. If heaps are too permeable the solution-ore contact time will be insufficient also resulting in reduced or slow recovery. Heap leaching operations can also be influenced in some situations by other parameters such as flow rate, concentration, particle size, mineralogy, etc.

Heap leach piles are heterogeneous and anisotropic porous media. The hydraulic conductivity of heap leach piles can vary substantially from point to point. This variation is inherent to the variability in the ore being mined. The latter is a combination of variations in the comminution of the ore as a result of crushing, loading, and dumping, and segregation and plugging of pore spaces that occur during placement.

Heap leaching aqueous solution reagents do not completely fill the pore spaces of heap leach piles. This is why ore heaps are said to be unsaturated (Kunkel, 2008). Ore heaps are also filled with air. Along with aqueous leaching solution and lixiviant flows, air flow is an essential element in heap leaching processing. Generally, the higher the oxygen level, the greater the mineral resource recovery is obtained. It is then unwise to apply too much leach solution (more than 60 to 76 percent of water saturation), since it will saturate the ore heap and drive out the oxygen.

Heap leaching solution flow in an unsaturated porous media and do not have the same pattern as might be expected. This is a much idealised flow regime. Depending on the hydraulic characteristic of the ore and the lixiviant application rate, the flow may occur as uniform wetting front, capillary fingering, viscous fingering, or a combination of these. Heap leaching solution flow patterns are well described in (Kunkel, 2008). The difference in flow patterns depends on the hydrodynamic instability prevailing in unsaturated porous media. The criteria for flow instability are well depicted in **Fig. 2.1**: flow instability occurs whenever the pressure head at the soil surface is smaller than at the wetting front [(b), Raats, 1973], flow instability occurs whenever the pressure gradient, G, at the wetting front opposes the flow [(a), Philip, 1975], and flow instability occurs whenever the hydraulic conductivity of the underlying coarse layer is larger than the average flux in the fine layer above [(c), Hill and Baker, 1990].

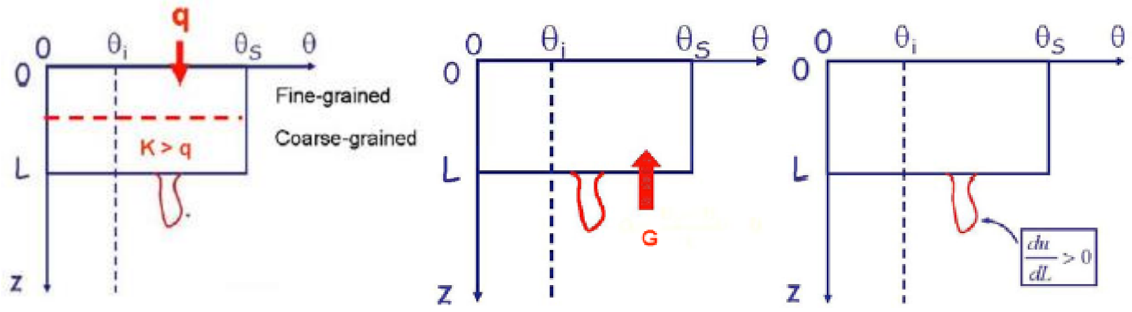

Figure 2.1 Stability criteria for flow in unsaturated porous media (Kunkel, 2008)

Kunkel (2008) stated that in general fingering flows are the most important flow patterns in heap leaching operations. This means that solutions do not generally flow evenly throughout the heap. They instead flow preferentially through distinct paths. It is then very important to obtain a relatively permeable and a uniformly structured ore heap before starting heap leaching operations. This will help avoiding as much as possible channelling and short-circuiting problems of leach solutions in the heap, and creates a uniform wetting pattern over the leaching ore. This is however very difficult to achieve as layers of coarse and fine textured ore inevitably develop within ore heaps. This is the result of the natural segregation processes that take place during ore placement (O'Kane, 2000). Segregation of heap ore will occur regardless of whether the ore is agglomerated or non-agglomerated. Clearly, this means that heap leach solutions will unavoidably follow preferred flow paths.

3. Plugging mechanisms in heap leaching processes

Flow conditions of heap leach piles are very complex and require a careful management in order to obtain excellent extraction kinetics and recovery of the mineral resources of interest. The major concerns faced by a heap leaching process operator are generally adequate flow and even or uniform flow of solution through the heap. An adequate flow is necessary for the heap to be leached in an economical time, while uniform flow is needed to allow all the ore to be leached thoroughly. The major negative contributor to the permeability ore heaps is the clogging or plugging of pore spaces of the heap pile. Various factors contribute negatively to the efficiency of ore heap's effectiveness in plugging pore spaces. The most predominant factors are heap compaction, migration of fine particles, large fractions of clays, agglomerate destruction under the effect of leaching solutions and dissolution-precipitation processes.

3.1 Plugging of pore spaces due to ore heap compaction

Compaction of ore heaps following careless or inadequate material placement practices can lead to major permeability problems. Permeability issues can also arise from ore material consolidation during the life of ore heaps. Depending on the type of ore used, compaction and/or consolidation will result in minor or significant reduction of ore permeability (Milczarek *et al*., 2013). This will have the effect of increasing the leaching the time and will lead to an incomplete recovery of mineral resources. It then follows that the method used to place the ore material on the leach pad is a major factor in the success of heap leaching operations.

3.2 Plugging of pore spaces due to migration of fine particles

Fine particles (particle having a size of the order of one micron) are amongst the major contributors to low conductivity of ore heaps during heap leaching operations. Fine particles in the ore can block inter-particle pore spaces, thus reducing the overall void spaces and therefore the permeability of ore heaps. Fine particles reduce the permeability of ore heaps mainly by migration of fines through porous media. The migration of fine particles may involve detachment of fines present in the pore spaces, entrainment of fines with the lixiviant flow, and finally capture and accumulation of fines at some pore spaces, in most cases constriction sites (Khilar and Fogler, 1998). The detachment of fines is mainly due to colloidal and hydrodynamic forces that are exerted on these particles.

3.3 Plugging of pore spaces due to the presence of large fractions of clays

Large fractions of clay minerals in ores may cause uneven solution distribution and plugging at the bottom of ore heaps during heap leaching operations (Vethosodsakda, 2012). Clay minerals often have a very small particle size, usually less than 2 microns, with a very high surface area (Connelly, 2011). Clay minerals can be classified as swelling and non-swelling clays (Mohan *et al*., 1993). Swelling clays are not desired in heap leaching operations as they undergo significant changes in volume with corresponding changes in their water contents (Yong *at al*., 2012). The volume expansion of clays is the consequence of effective repulsion between clay particles. The later is a result of interactions between contiguous clay particles under the effect of the ionic composition and pH of the lixiviant. Clay minerals can reduce the permeability of ore heaps through the following three mechanisms (Mohan *et al*., 1993). (a) Migration of clay particles: changing ionic conditions can cause the release of clays from pore walls and result in plugging of flow channels in the heap. (b) Swelling of clay particles: Swelling: changing ionic conditions can cause swelling of clays lining the pores and therefore reducing cross-sectional area for flow. (c) Swelling-induced migration of clay particles: changing ionic conditions can cause swelling of clays lining the pore walls and therefore dislodging fines in the process. It is therefore important to acquire a better understanding particularly, the rheological aspect prior to conducting actual agglomeration of high swelling clay content ores.

3.4 Plugging of pore spaces due to agglomerate destruction under the effect of leaching solutions

Leaching solution may dissolve and destroy the agglomeration bonding within the agglomerates during heap leaching operations. As results, agglomerates are disintegrated and insoluble fine particles generated are released into the liquid flow system. The destruction of agglomerates can also be enhanced by a proper curing of agglomerates was not performed.

3.5 Plugging of pore spaces due to dissolution-precipitation processes

In heap leaching operations, the lixiviant is consumed by both the gangue and mineral resources of interest. Precipitation reactions following gangue-lixiviant reactions often occur in heap leaching processing. The precipitate products formed such as gypsum, jarosite, silica…can have significant negative effects on leach permeability by prematurely plugging up of the pores in the heaps. Precipitate products can act as retardants to the flow of leach solutions in the heap. They can also increase the risks of plugging and related issues. If an appropriate lixiviant concentration and an optimised irrigation system are not used, further accumulation of products precipitated in the pore spaces will result obviously in a gradual decrease of the extraction kinetics and the mineral resource recoveries. To this must be added the high risk of ponding.

4. Plugging reduction techniques

Existing plugging reduction techniques are more proactive than reactive. As the saying goes, "an ounce of prevention is worth a pound of cure". All preliminary work (agglomeration, ore placement, irrigation system optimisation and selection of the lixiviant…) must be carried out carefully to avoid future problems of plugging of pore spaces.

4.1 Ore agglomeration techniques

Large fractions of fines and clays in heap leaching operations may cause low mineral resource recoveries due to non-uniform wetting patterns over the heap leaching ore and plugging of pore spaces. This leads to the reduction of heap permeability and/or channelling of lixiviant flow as it was already shown herein. These problems are mitigated to some extent by the agglomeration pre-treatment of the ore prior to heap leaching. The agglomeration process is intended to minimize segregation of coarse particles and to reduce the migration of particles in the ore in a heap, as well as to reduce the leaching time.

The use of agglomeration should however be justified only if the ore processed contains a large proportion of fines smaller than 50–75 µm (Heinen *et al*. (1979); McClelland (1986); Garcia and Jorgensen (1997); Kinard and Schweizer (1987)). Garcia and Jorgensen (1997) recommended agglomeration for ores containing more than 5 % of less than 74 µm of fines.

Agglomeration is generally achieved by adding water or moisture and a binding agent to the ore in agglomeration equipment. In some cases, the lixiviant may also be pre-mixed with the ore fines during agglomeration to achieve a more concentrated, homogeneous mixture and hence, an improved percolation; this is referred to as curing. Well manufactured agglomerates should not segregate or disintegrate in fine particles under normal heap leaching operating conditions. The performance of an agglomeration process is closely related to the nature of the processed ore. It is therefore important to conduct a comprehensive physical, chemical, and mineralogical characterisation of the ore to be leached, prior to agglomeration. The characterisation of ores generally comprises a series of mechanical and hydraulic tests (Lupo, 2012): particle size distribution, specific gravity, silt vs. clay content, Atterberg limits of plasticity and solidity, weathering and swelling characteristics, triaxial strength and internal friction angle, and permeability. The results of these tests can help define optimum operating conditions under which agglomeration, ore placement and heap irrigation should be conducted. They can as well be used to select the appropriate lixiviant.

As much as agglomeration is concerned, following parameters are often regarded: moisture level, binder type, binder dosage, curing time, agglomeration equipment type, and residence time.

4.1.1 Moisture level

Initial binding mechanisms in the agglomeration process often involve interfacial forces such as capillary forces. These forces are strongly related to the amount of moisture in the ore treated. It is therefore important to analyse ores in terms of the initial amount of moisture prior to conducting agglomeration. Each ore has a level of residual moisture called liquid retention capacity. This can be defined as the amount of moisture held in ore particles after the excess liquid has drained away. During heap leaching operations, the amount of moisture should be well regulated. If it goes beyond the liquid retention capacity, the agglomerates formed will be unstable and there will be a formation of mud. Similarly, moisture levels below the liquid retention capacity may not produce sufficient capillary bonding for desired agglomeration. An appropriate amount of moisture should be then used to promote the creation of strong liquid bridges between the particles, and also the obtaining large and stable agglomerates.

4.1.2 Binder type and binder dosage

The selection of the proper binder type and dosage is of critical importance in producing high quality agglomerates. A good binder is expected to function satisfactorily over a large range of pH and temperature. In addition to this, in view of the large quantities of ore handled in heap leaching operations; the binder must be low cost and efficient at low dosages. The binder developed need also to be environmentally friendly. The agglomerate strength is dependent on the type of bonding produced by the binder. Bonding interfacial forces are classified as capillary forces, Van Der Waals forces and adhesion and cohesion forces. The most frequently used liquid bridge for copper ore agglomeration is sulphuric acid leach solution, which forms liquid bridges thanks to capillary forces established between adjacent particles. Though leading to agglomerates of poor stability, the use of sulphuric acid still justified in copper heap leaching in that satisfactorily alternative inexpensive and acid resistant binders have not yet been developed. Some high performance binders (polyvinyl acetate, tall oil pitch, stucco, various polyacrylamides) are reported in the literature, but their use on a large scale basis need to be confirmed. In gold and silver heap leaching operations, Portland cement type II is the most used binder. Agglomerates obtained with Portland cement offer many advantages over agglomerates formed using liquid bridges. However, when cement or lime binders are used in acidic conditions, which is the case of copper heap leaching operations, precipitation of gypsum and jarosite occurs (Bouffard, 2005). This requires beforehand that factors that affect binder performance be known and controlled in order to achieve the maximum strength and thermal resistance in the agglomerates.

4.1.3 Curing

It is common to pre-treat ores, especially in copper heap leaching, with acid solutions prior to actual agglomeration. This practice is termed curing. This is aimed at accelerating the extraction kinetics and subsequently increases the mineral resource recovery. The curing process involves the addition of a highly concentrated sulfuric acid to the copper ore during agglomeration. This allows earlier irrigation of the heap, transforming the initial copper species into new copper species, which are easier to solubilise once the leach solution is provided to top of the heap. This can be explained in that highly concentrated sulphuric generally dissolve more iron that enhances dissolution of copper minerals. Concentrated sulphuric acid also stabilises silica by preventing the formation of silica gels which can lead to loss of reagent during the organic solvent extraction step (Patiño, 2004). There is however some uncertainty regarding the real effect of the ferric/ferrous ratio on copper solubilisation during the curing process. The proper dosing of sulphuric acid during curing and the minimum rest time for adequate curing are dependent on the gangue mineralogy of each particular ore and should be determined for every particular deposit (Baum, 1999).

4.2 Ore placement techniques

The main objective of heap construction is to obtain the most homogeneous heap possible. It is therefore important to well select the ore heap placement technique. A careless technique can lead to heap compaction and particle size segregation and related plugging issues. Ore heaps can be built according to the following approaches: truck damping and dozing, plug damping and conveyor system. Since trafficking of trucks and labours on top of the heap is to be avoided by all means to minimise the compaction of heaps, the conveyor system approach has received widespread acceptance in heap leaching operations. This technique involves hauling and stacking ore on heaps using belt conveyors. It also has the advantage to making the piling operations to be simple and quick. Basically, the front end of the system usually consists of a short fixed conveyor that receives prepared ore from a crusher, agglomeration equipment, or a stock pile through a feed hopper. The conveyor then transfers the material to a mobile radial-arm stacker by means of a series of movable belt conveyors. The great flexibility of the stacker allows the heaps to be formed uniformly and without compaction to almost any height desired. Moreover, conveyor systems can handle any feed ore, from primary crushed ore to agglomerated tailings.

4.3 Selection and application of lixiviant

Now that the ore heap has been built, an appropriate lixiviant needs to be utilised to optimise the mineral resource recovery. The concentration of the lixiviant should be controlled to allow some degree of selectivity of valuable metal or metals that are to be recovered. A high concentration of the lixiviant will undoubtedly lead to a significant dissolution of the gangue. This will enhance the threat of plugging of pore spaces by potential precipitate products such as gypsum, silica and jarosite in the heap. It is therefore important to fully characterise the ore and to know the chemistry of the lixiviant. This will help predicting how the mineral resources, the gangue and the lixiviant inter-react and what would be the reaction products formed.

The lixiviant application technique is also an important point to consider for the success of heap leaching operations. The leach solution and the lixiviant do not seep as a uniform vertically downward flow regime through the ore heap. They flow preferentially in the more conductive layer, while potentially leaving areas within the heap unleached. The preferred flow path of the lixiviant is not dependent entirely on the physical properties of each layer, but also on the lixiviant application rate. It is then highly recommended to optimise the application rate of the lixiviant, as too much increase of the lixiviant application rate will create saturated zones near the base of the pad, and that could induce slope failure. Migration of fine particles in heaps is also often due to improper lixiviant application technique or rainfall (Phifer, 1988). Low application flow rates of the lixiviant can generally carry enough momentum to transport fines up to 0.3 meters after agglomeration. Fines will go even far with increasing application flow rates.

The irrigation system needs also to be looked at to ensure that the ore heap receives uniformly the lixiviant. To this end, the old sprinkling irrigation technique is being progressively abandoned in many heap leaching operations in favour of the drip irrigation technique. This consists in applying the leach solution on the top of the highest lift of the heap. The leach solution then chemically bonds with the ore as it gradually percolates through the layers of the ore heap. **Fig. 4.1** illustrates the concept of a typical heap leaching operation that uses drip irrigation. Ideally, the pregnant solution flows by capillary action to the bottom of the heap to the geo-membrane liner. The solution then flows by gravity to holding ponds for temporary storage. It is finally pumped to the tank houses where valuable metals are extracted. The spent solution is re-circulated to the top highest lift of the heap.

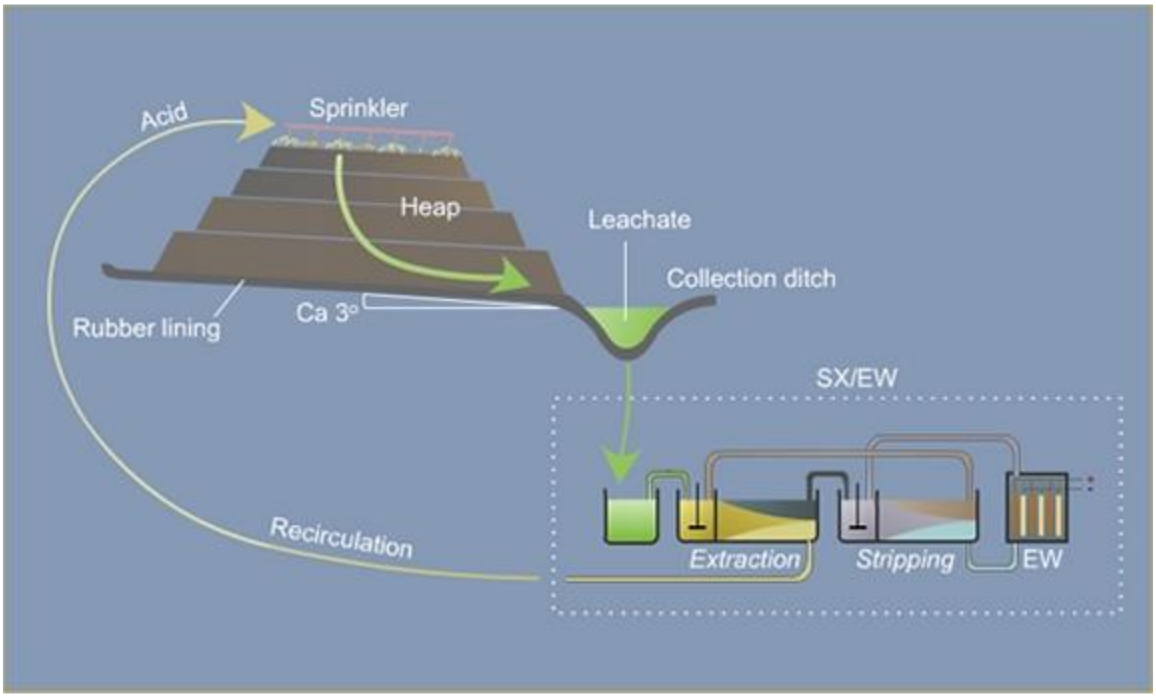

Figure 4.1 Illustration of a typical heap leaching operation using drip irrigation technique (Oremax™, 2014)

Conclusion

Heap leaching is known as one of the least expensive metallurgical methods for treating low-grade ores. This is however true only if a correct understanding of the geology, mineralogy of correctly selecting representative samples of the ore to be processed is obtained. This often requires a significant investment in research. To this is added the lengthy testwork program related to agglomeration, ore placement and leaching optimisation. A botched study on the feasibility of the heap leaching process can lead to plugging of ore heap pores and related issues such as channelling and poor mineral resource recovery, and to some extent to the stoppage of the project. Physical methods can be used to determine the extent of plugging of ore heaps. These include throughput testing, intermediate pressure and a comparison of particle populations in the feed and the leach solutions. These methods are however only indicators of the extent of plugging mechanisms. The best way to deal with plugging mechanisms is to prevent them.

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