Effect of primary grind particle size distribution on the dewatering performance of hydraulic dewatered stacking

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ABSTRACT

Maximizing the water recovery from tailings storage facilities, while minimizing risks of managing a wet tailings dam, has been an aim from mining companies for many years. Different technologies have been developed for this purpose from conventional, high-rate, high density and paste thickening to filtered tailings. As the water recovery from these technologies increases also does the costs associated with the implementation of these water recovery unit operations.

Challenges still remain for high throughput copper porphyry deposits, especially in the Andean Region, were water is scarce. Efficient and sustainable water management with minimal impact in the surrounding communities is one of the key value drivers for any operating facility as pressure for decreasing the use of continental water for mining activities increases.

In the present context, AngloAmerican has engineered a co-disposal tailings management system called Hydraulic Dewatered Stacking (HDS) that involves fines-free sands and fine tailings creating a 3-dimensional drainage system that promotes in-situ dewatering of the wet tailings and consolidation of the materials. The HDS concept has been proved in a 150,000 m^3 demonstration plant at El Soldado mine. The fines-free sands are obtained from a Coarse Particle Flotation unit that recovers coarse, partially liberated copper sulphides and obtaining a fines-free barren sand.

Every operation has different primary grind size targets and breakage characteristics, shaping the particle size distribution (PSD) of the grinding circuit product that feeds the flotation circuit. Five current copper porphyry concentrators, with a throughput > 95 kt/d have been investigated to understand the effect of different PSD in the applicability of HDS. The P_{80} of the 5 operations vary from 145 µm to 250 µm.

Fines content on CPF sands is independent of the primary grind target, with particles below 75 µm being less than 0.5% for all the operations evaluated. The permeability increases by 54% as the primary grind size increases from 145 µm to 250 µm. The values validate the intended use of CPF sands coupled with fine tailings to improve dewatering and consolidation with HDS.

This evaluation confirms that the quality of the sands generated by CPF for any primary grind target is appropriate for HDS, with the permeability being within a range that benefits dewatering and consolidation.

INTRODUCTION

Complex orebodies of the future will need mining companies to adopt new technologies to cope with lower grades, increasing ore competency/hardness, water scarcity and social pressure to reduce the energy and water consumption of the mining operations whilst making this future ore treatment economically viable.

These different new technologies focus on rejecting waste or low grade material prior to enter the concentrator such as Bulk Ore Sorting (BOS). Once the ore feeds the concentrator, the aim is to reduce the specific energy consumption to liberate the minerals of interest. One option is to use more energy efficient technologies such as High Pressure Grinding Rolls (HPGR), Microwaves or Dry Comminution, being the selection against typical tumbling mills being one that maximizes the economic benefit.

Independent of the comminution technology to achieve the required liberation, another option that has been getting more traction since its inception in the hard rock industry in 2018 is coarse particle flotation (CPF or CPR), increasing the target P_{80} of the grinding circuit. CPF is already installed or under construction at the following operations: Cadia, Kennecott, El Soldado, Mogolakwena, Quellaveco and Carrapateena, with several other operations having advanced engineering to include coarse particle flotation in their existing operations or expansion projects.

Implementing CPF potentially gives the following advantages: increase in recovery, reduction in operating costs by coarsening the primary grind, increase throughput by liberating already constrained ball mills and opportunities to improve the water or energy efficiency. Generally, the adoption of this new flotation approach focus on the increase of metal produced at a reduced energy consumption per metal produced. Not the same attention has been dedicated to explore the increase in water recovery by producing barren sands, < 5% below 75 µm as part of the process.

AngloAmerican as one of the early adopters of coarse particle flotation has developed a process called Hydraulic Dewatered Stacking (HDS) that uses the fines-free barren sands produced in CPF as draining material, co-disposing wet tailings on top of contiguous sand blankets and channels, creating a drainage system that promotes in situ dewatering. The HDS method delivers a tailings deposition system that enhances drainage and consolidation, increasing overall water recovery and reducing risks of wet Tailings Storage Facilities.

HDS has already been commissioned at the El Soldado large-scale demonstration and results of the first 9 months of operation are reported in Newman et al. (2023). The free-fines sands are obtained from the largest industrial HydroFloat™ installed and commissioned (Arburo et al. 2022). The El Soldado operation has a base case P_{80} of 200 µm, previous implementing CPF, this P_{80} will be different for other operations, and not only the target grind size, but the Particle Size Distribution (PSD).

The aim is to study the effect of different particle size distributions on the quantity and quality of the CPF sands, and the effect on hydraulic conductivity when adopting HDS coupled with the CPF barren sands. Mill product PSD of five high throughput concentrators located in the Andean region are evaluated within the context of HDS application.

COARSE PARTICLE FLOTATION

Since the inception at Broken Hill Proprietary Limited (BHP) in 1905 of froth flotation, this has been the preferred processing route to treat a wide variety of commodities such as the copper sulfide minerals present in the Andean region of South America. This beneficiation method relies on having mineral surface exposure (liberation) onto which selective reagents attach to the minerals of interest, making their surface hydrophobic. Once the surface of those sulfidecontaining particles has become hydrophobic, they will attach to air bubbles in the turbulent zone of a mechanical flotation device and ascend to the froth zone where the concentrate is recovered, as shown in Figure 1.

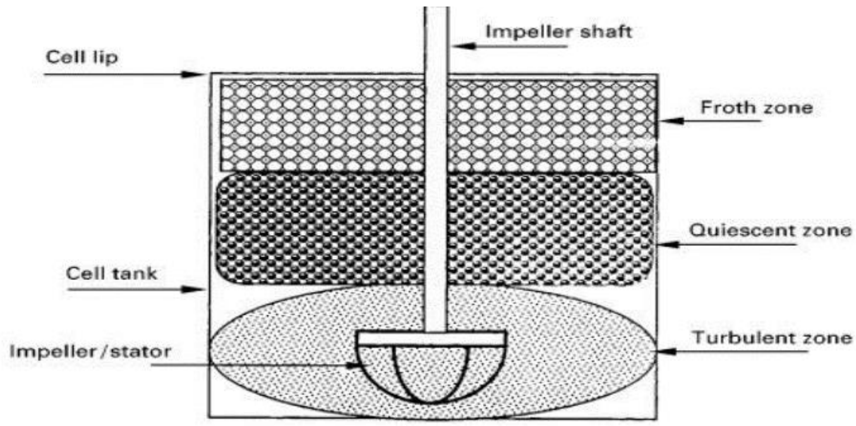

Figure 1. Hydrodynamic zone in a mechanical flotation cell, Gorain et al. 2000

Froth flotation delivers high minerals recovery within a size range, typically 10 µm to 150 µm. At very fine particles, < 10 µm, recoveries reduce due to slower flotation rates, at coarser sizes, > 150 µm, mineral recovery is reduced because poor liberation, bubble particle detachment, insufficient transport of coarser particles from the quiescent zone to the froth phase or inefficient transport of coarse particle-bubbles in the froth phase due to bubble breakage and particle drop back. The recovery per size fraction is shown in Figure 2.

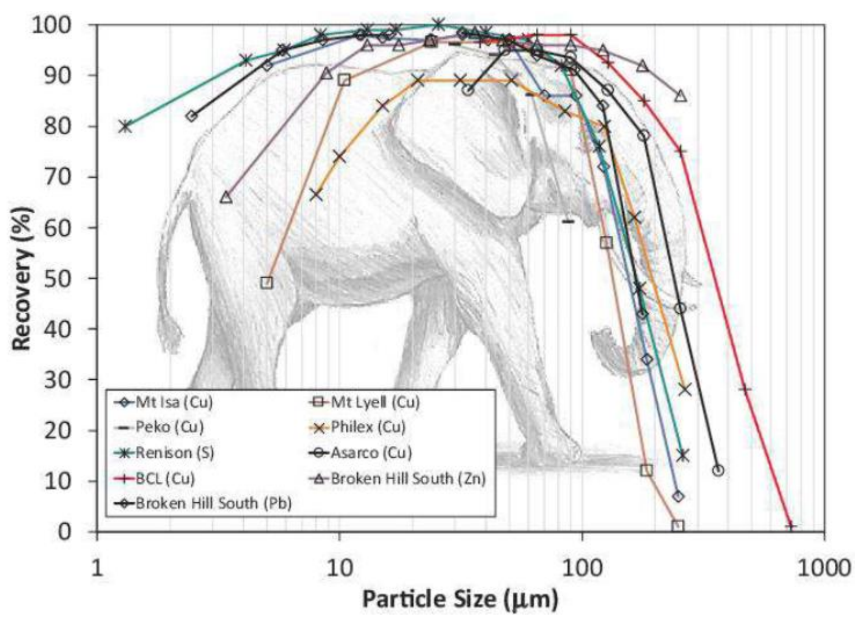

Figure 2. Flotation elephant curve, Lynch et al. 1981

Maximizing recovery whilst reducing energy consumption by coarsening the primary grind target has been an area of increasing interest during recent years, to reduce the specific energy consumption (kWh/lb Cu produced), reduce the carbon footprint (tCO2 /lb Cu produced), while increasing recovery and potentially reducing water consumption by having a coarser PSD in the final tailings.

As mentioned before, coarse particle flotation is an area of increasing interest in the development of concentrators. This already been adopted in Cadia, Quellaveco, El Soldado, Mogalakwena. To achieve flotation at a coarser grind size than conventional flotation several technologies are available, including Jord NovaCell™, Eriez HydroFloat™, Cidra P29 Technology™, FLSmidth coarseAIR™ and others. This paper will focus on the Eriez HydroFloat™ which currently has the most significant installation list, and it's been operated at El Soldado, where the CPF tails (sands) have been used in the HDS demonstration.

The HydroFloat™ cell enables the recovery of coarser particles at lower liberation classes compared to mechanical cells by exploiting the following mechanisms:

- Particle-bubble attachment in a fluidized bed
- Quiescent flotation conditions to ensure particles and bubbles remain attached
- Upflow of water for hydraulically assisted flotation
- Overflow of a liquid phase from the cell without a froth interphase to minimize particle drop-back

Figure 3 shows a simplified schematic representation of the Eriez HydroFloat™ cell and some key operating factors to achieve the target recovery, these being the following:

- Teeter bed level. Dictates the residence time available for bubble-particle attachment and determines the distance the agglomerates travel from the top of the teeter bed to the overflow
- Teeter water. Help establish the teeter bed and assist the hydraulic transport of the agglomerates to the surface
- Air input. To have flotation, any flotation, bubbles are needed to attached the liberated particles to those bubbles, creating the SG difference, that coupled with the teeter water, creates the upflow of the bubble-particles necessary for the hydraulically-assisted separation to occur.

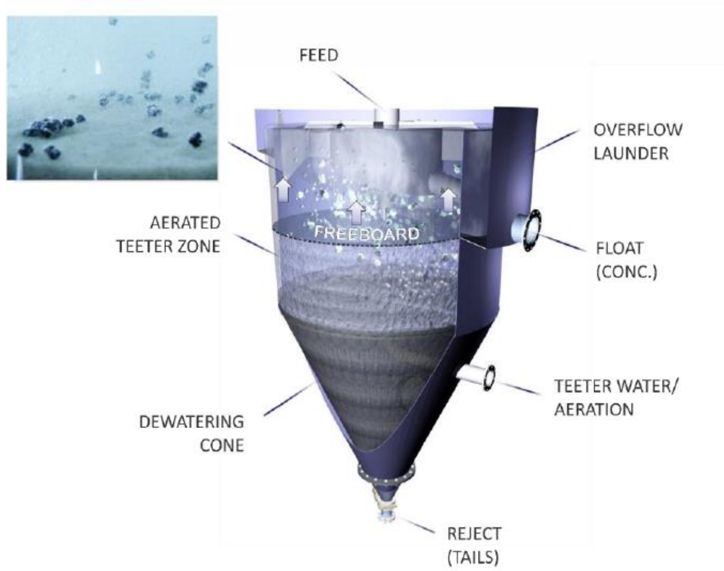

Figure 3. Simplified Schematic Eriez HydroFloat^{TM}, Miller et al. 2016

Figure 4 presents a typical recovery per size curve of a copper porphyry for both, a mechanical or conventional flotation and a coarse particle flotation (CPF or CPR)[1]

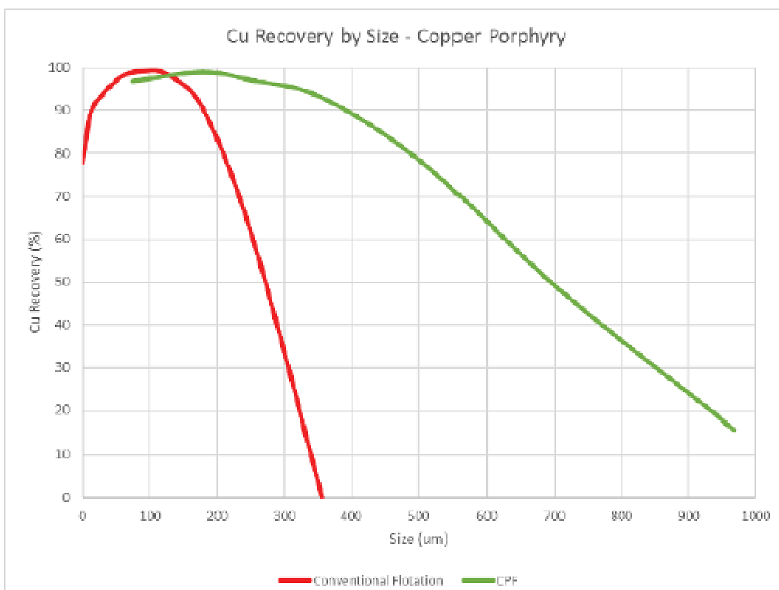

Figure 3. Typical recovery per size curve

There are two circuit configurations installed in hard rock applications:

- Coarse Gangue Rejection (CGR) or Pre-Rougher Mode

[1] CPF (coarse particle flotation) or CPR (coarse particle recovery) are the same process

- Tails Scavenging (TS) or Rougher Tails Mode

Both flowsheets consider an initial classification to deslime the feed to the HydroFloat™ Cell, achieving a target of <10% below 75 µm. Once the fines content is below the required threshold, it feeds the flotation cell, with teeter water being fed at the bottom of the cell generating an upflow, recovering the coarse-poor liberated copper sulfides on the top of the cells and reporting barren sands in the cone of the flotation cell.

These barren sands are the foundation for the HDS, and their particle size distribution and quantity available will depend on the grinding circuit PSD.

HYDRAULIC DEWATERED STACKING

Hydraulic Dewatered Stacking (HDS) is an engineered co-disposal approach developed and patented by Anglo American that uses a fines-free sands, derived from the tailings themselves, to deliver drainage channels throughout the tailings facility, accelerating consolidation and dewatering (Newman et al., 2023). The fines-free sands are deposited in contiguous layers and channels and exploits the higher horizontal permeability present in tailings facilities (Naeini et al., 2018).

The HDS was hypothesized, developed and demonstrated by Anglo American between 2019 and 2024 at their El Soldado operation in Chile (150,000 m^3 capacity greenfield tailings facility) where promising findings and outcomes have been observed, e.g. desaturation capacity of the materials, suction development, benefits of promoting horizontal drainage paths, among others. The results of the first 9 months of operation of the facility are reported in (Newman et al., 2023).

(Bustamante et al., 2024) studied the effects of increased fines content in draining-sands that showed that increases in fines content in CPF sands in the range from 0% to 10% resulted in a decrease of two order of magnitude in the coefficient of hydraulic conductivity.

The proof of concept has been done, as mentioned before, in El Soldado mine that included CPF in their flowsheet to generate the fines-free sands. Determination of the primary grind PSD impact on the coefficient of hydraulic conductivity has not been investigated.

SANDS CHARACTERISTICS AT DIFFERENT PRIMARY GRIND PARTICLE SIZE DISTRIBUTION

To evaluate the effect of the primary grind PSD on the dewatering performance of hydraulic dewatered stacking, five operating copper concentrators of the Andean regions were evaluated. Each of these copper concentrators have an annual throughput > 34.5 Mtpa. Table 1 presents the location, throughput and P_{80} of the copper concentrators to be evaluated.

Plant	Country	Throughput, kt/d	Grinding P80, µm	Cu head grade, %
Plant 1	Chile	126	145	0.80
Plant 2	Chile	116	170	0.55
Plant 3	Perú	127.5	186	0.54
Plant 4	Chile	160	230	0.93
Plant 5	Chile	100	250	0.65

Table 1. Copper Concentrators Flotation Feed Parameters

For each concentrator, operating P_{80} was coupled with Rossin-Rammler to generate the particle size distribution curves shown in Figure 4. The curves are typical for primary grind cyclone overflow and aligned with other copper concentrators that have CPF incorporated like Cadia (Jaques et al., 2021), were the % passing 38 µm (-#400) is between 40%-50% depending on the primary grind. The coarser the primary grind, the fewer amount of particles below 38 µm.

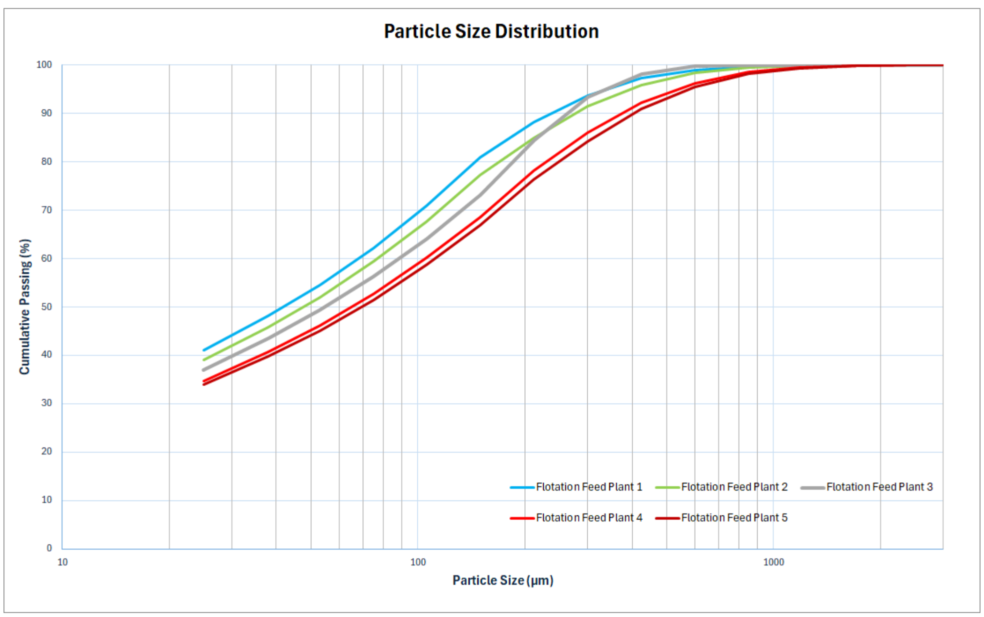

Figure 4. Flotation Feed Particle Size Distribution

For the PSD´s presented above a process design criteria were developed to size equipment, but more importantly perform a mass balance per size fraction throughout the coarse particle flotation circuit. The flowsheet configuration considered is Tail Scavenging as it is simpler and is currently the more adopted configuration in the industry. Figure 5 shows a simplified CPF flowsheet configuration, and the unit operations involved.

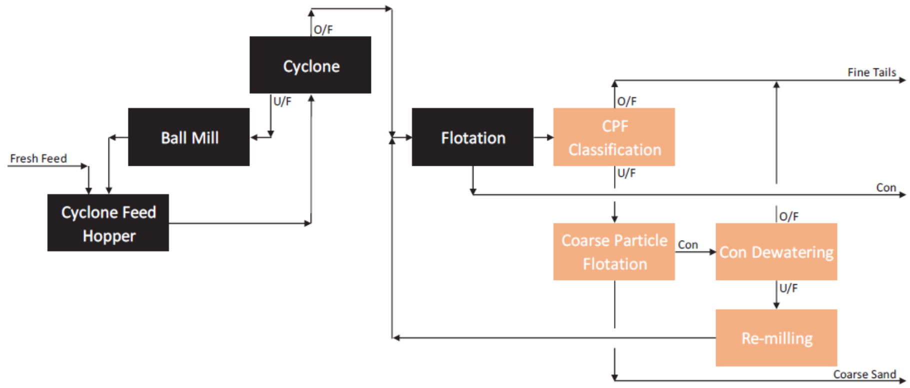

Figure 5. Rougher Tailings (Scavenging) Flowsheet, Pyle et al., 2023

The flowsheet selected considers the following unit operations:

- CPF Classification
    - Conventional flotation tailings, typically rougher tailings, are deslimed before feeding the HydroFloat^{TM} cell. Usually, the HydroFloat^{TM} feed requirements target <10% mass passing 75 µm
    - Reducing fines reporting to the flotation cell minimizes the impact of fine particles on the fluidized bed and entrainment of fine particles reporting to the concentrate
    - Different classification circuit designs are available to achieve the fines target. Early applications such as Cadia T3, Kennecott and Quellaveco use Crossflow classifiers coupled with an early stage of cyclone classification.
    - Newer generation CPF projects are proceeding with either two stages of cyclone classification or sand cyclones such as FLSmidth cyclowash or Weir DE cyclone
- Coarse Particle Flotation
    - Once the rougher tailings are conditioned to the right particle size distribution and reagents added, they feed the HydroFloat^{TM} cells
    - Key aspects to design this system are the following: feed solids loading rate (t/m^2h): feed solids percentage (%), teeter water ratio ($m^3/h/m^2$), tails solids percentage (%)
- CPF Concentrate Dewatering
    - The CPF concentrate needs to be deslimed before being reground to a specific grind size target
    - The desliming or dewatering is usually performed in cyclones, where the OF reports to final tailings and the UF to the concentrate regrind circuit
- CPF Concentrate Regrind
    - Once the CPF concentrate has been dewatered, it needs to be reground to a specific target before reporting to either the existing rougher circuit or to a dedicated flotation stage

- Different regrind technologies are available for duty. The mill selection will depend on factors such as grind size target, Capex, Opex or GHG[2] emissions. The mill types can be ball mills, VTM´s or HIG mills (VRM), where the selection of the technology will depend on the directions of the project such as capital costs reduction, less energy consumption, no use of forged steel media or others.

For this paper, the interest is to generate sands from Coarse Particle Flotation, hence no analysis or equipment sizing has been done on CPF concentrate dewatering or regrind. Table 2 presents simplified design criteria to size the circuit and generate the data to obtain the PSD and mass balance of the generated sands and final tailings.

Parameter	Unit	Value
Feed tonnage	kt/d	100
Run time	%	92
Feed tonnage	t/h	127.5
Solids SG	t/m3	2.7
Classification		
Type	-	DE
Feed Solids Content	%	30
U/F Solids Content	%	71
Passing 75 µm	%	< 10
HydroFloat		
Cell diameter	m	5
Solids feed loading rate	$t / m^2 h$	16.5
Teeter water	$m^3 / m^2 h$	20
Sands Solids Content	%	62

Table 2. Simplified CPF Process Design Criteria

From the simplified process design criteria, besides the equipment sizing, a mass balance per size fraction was obtained for the five operations evaluated. Table 3 presents the general mass balance and P_{80} of the product streams of CPF.

[2] GHG: Greenhouse Gases

Parameter	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Throughput	t/h	4,529	4,529	4,529	4,529	4,529
Primary grind target	%	145	170	186	230	250
Sands produced	t/h	696	802	724	977	1,053
Sands P_{80}	µm	402	445	373	565	588
Fine tailings produced	t/h	3,705	3,639	3,735	3,421	3,374
Fine tailings P_{80}	µm	71	69	97	90	89
Sands:Tailings ratio	%	18.8	22.1	19.4	28.6	31.2
Sands < 150 µm	%	12.2	9.6	8.9	4,7	4,3
Sands < 106 µm	%	1.5	1.2	2.2	1,0	0,9
Sands < 75 µm	%	0.4	0.3	0.4	0.3	0,3

Table 3. Sands and Tailings characteristics

From Table 3 it can be seen:

- As the primary grind target is increased, a higher production of sands, and coarser sands P80 is obtained, except for plant 3 that has a slightly different primary grind particle size distribution
- The sands produced by CPF have less than 0.5% below 75 µm, independent of the primary grind target. The sands PSD is directly related to the restriction of fine particles in the feed of the cells. It is expected that independent of the process facility, the particles below 75 µm are negligible for CPF sands
- The fines tailings P_{80} is considerably lower than the primary grind target due to most of the coarse particles reports to the HydroFloat™ cells and then are discarded as barren sands. The ratio of sands to fine tailings and the PSD distribution of those fine tailings are key on the performance of HDS

Figure 6 shows the PSD curves from the generated sand and the fine tailings.

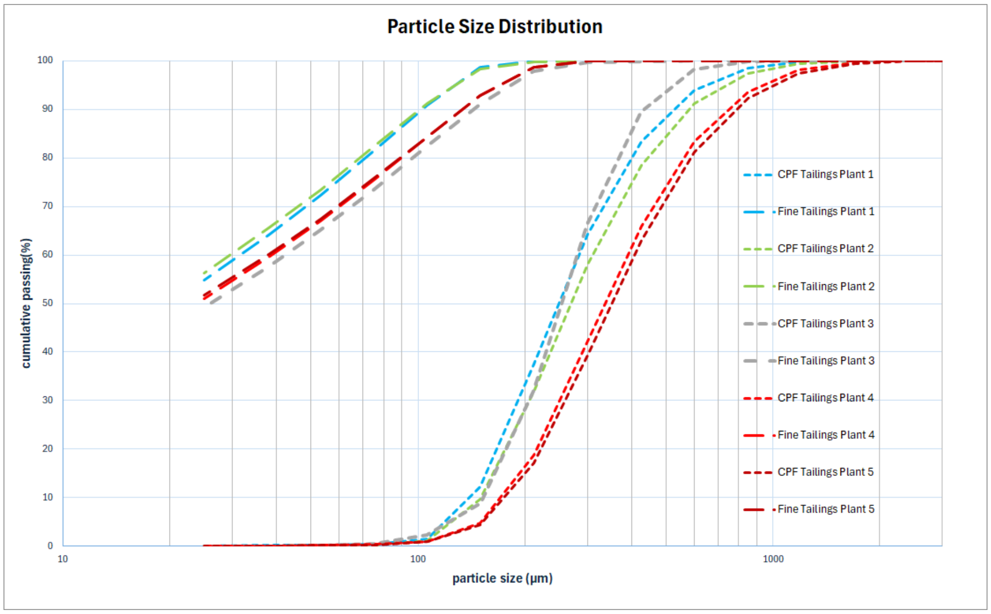

Figure 6. Sands and Fine Tailings Particle Size Distribution

From Figure 6 it can be seen:

- For the CPF sands up to a 100 µm, the amount of particles in that size fraction are negligible and are independent of the primary grind particle size distribution
- For the fine fraction of the tailings, below 38 µm there is a 10% difference in the extent of particles below that size fraction between a typical primary grind, 150 µm – 180 µm, and a coarser primary grind > 230 µm. The effect of the higher fines content on the tailings for hydraulic conductivity needs to be investigated.

HYDRAULIC CONDUCTIVITY AT DIFFERENT PRIMARY GRIND PARTICLE SIZE DISTRIBUTION

The hydraulic conductivity (or permeability) of granular soils depends mainly on the cross-sectional areas of the pore channels.

Extensive investigations of filter sands by Hazen (1892) led to the correlation of permeability with the square of its effective grain size $(D_{10})^2$, via the parameter C_e (Terzaghi, 1996), where D_{10} is the particle size corresponding to 10% finer on the cumulative particle-size distribution curve.

The Hazen ratio was obtained for the design of sand filters for water purification, which means that the sands used have very specific characteristics, e.g. loose, clean, and with low uniformity coefficients (Cu). Several authors state that the equation is valid for D_{10} values between 0.1 mm and 3 mm; and for permeability values greater than 10^{-3} cm/s. This is consistent with the parameters of the CPF Sands as shown in Table 4 and Figure 7.

The range of the parameter C_e used in this paper was correlated considering the results of measured permeabilities and granulometries of the CPF Sands, previously reported by Anglo-American from their Mogalakwena and El Soldado projects (Newman et al, 2022; Musso et al, 2023), where permeabilities of 2.00E-02 and 3.39E-02 cm/s, respectively, were reported. At the same time, the parameter C_e typically varies between 50 and 200 (Terzaghi. 1996), which is also consistent with the results obtained.

Parameter	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
USCS Classification (ASTM D 2487)	-	SP	SP	SP	SP	SP
Cu, Coefficient of uniformity	-	2.03	2.07	1.85	2.27	2.31
Cc, Coefficient of Curvature	-	0.93	0.91	0.98	0.95	0.95
D_{10} grain size	µm	141	151	153	173	177
C_e (Hazen)	-	118 to 183 (values estimated from permeability tests)				
$k = C\cdot(D_{10})^2$, estimated permeability	cm/s	2.4E-02 to 3.6E-02	2.7E-02 to 4.2E-02	2.8E-02 to 4.3E-02	3.6E-02 to 5.5E-02	3.7E-02 to 5.8E-02

Table 4. Estimation of hydraulic conductivity of the CPF Sands

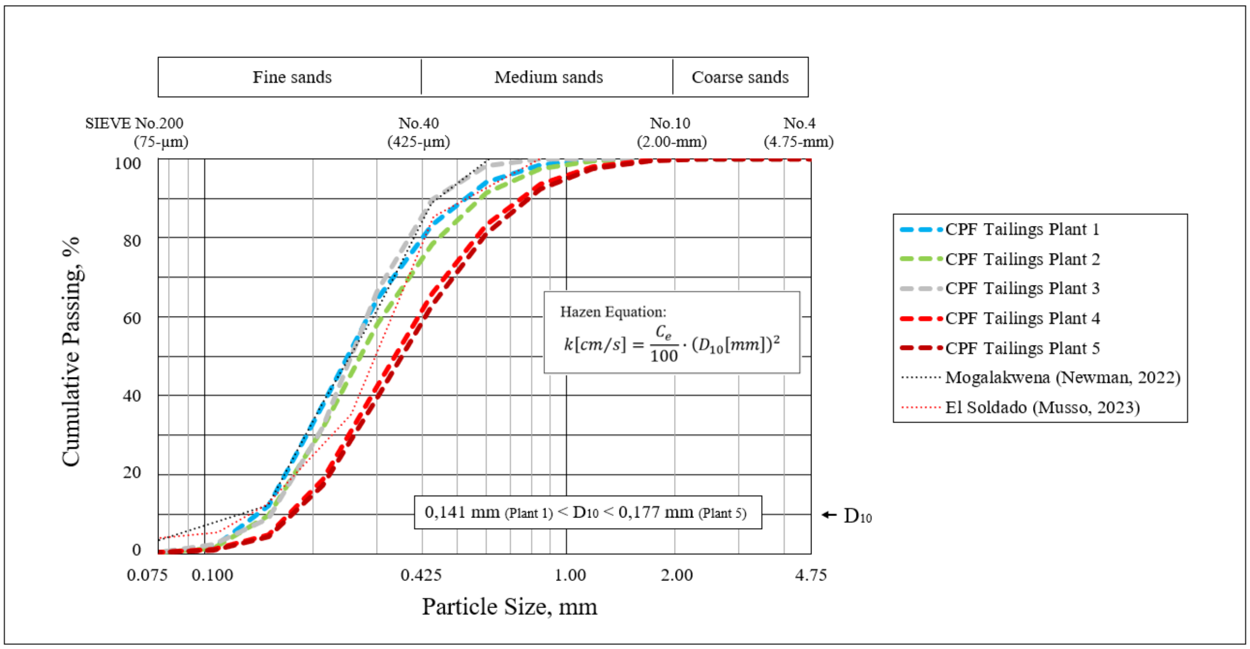

Figure 7. Analysis of D10 diameter of the CPF Sands

As can be seen from Table 4, the range of permeabilities estimated for the CPF Sands is consistent with their intended use as a drainage material, to create preferential flow paths within the tailings, improving dewatering, water recovery, and consolidation of the co-disposed tailings.

CONCLUSIONS

The effects of the primary grind PSD on the quality of the sands generated for 5 copper porphyry operations in the Andean Region by the implementation of CPF in tailings scavenging, Because of the content less than 75 µm required as feed material to the HydroFloatTM cell, there is negligible difference on the extent of particles below 75 µm in the generated sands, less than 0.5%. The differences mainly being the sands generated respect to the concentrator fresh feed, increasing from 18.8% for a primary grind target of 145 µm to 31.2% for a target of 250 µm.

Since the PSD of the sands is consistent below 106 µm, independent of the fresh feed primary grind target, the effect on permeability is generated by the fines tailings PSD. The modelling suggests that permeability increases by 54% as the primary grind size increases from 145 µm to 250 µm. The values validate the intended use of CPF sands coupled with fine tailings to improve dewatering and consolidation with HDS.

This evaluation confirms that the quality of the sands generated by CPF for any primary grind target is appropriate for HDS, with the permeability being within a range that benefits dewatering and consolidation.

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