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Handling dewatered tailings: the three root causes of poor material discharge and bin hang-ups

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Abstract

Dewatered tailings can be among the most difficult flowing bulks solids found in the mining industry. Understanding the scientific principles that guide good bin and feeder design for difficult flowing cohesive materials, such as dewatered tailings, is key to knowing how to design an appropriate storage and feed system capable of reliably handling these materials. In the late 1970s, Kamengo launched a 15-year research programme to understand and resolve the root causes of bin plugging, including for handling difficult flowing cohesive bulk solids such as dewatered tailings.

The research showed that good bin design centres on choosing the correct geometry for the storage bin using the flow properties of the stored material. The standard for a correctly designed storage bin is that with the feeder removed, it should self-empty with only the aid of gravity.

The research also showed that the feeder can be a significant culprit in creating plugging problems in a storage bin – including storage bins with correct geometry. First, conventional feeders have a tendency to compact the stored material. With many cohesive bulk solids, when you compact them, they gain strength very quickly. And the more shear strength a bulk solid has, the wider the opening it can bridge over. When compacted enough, a cohesive bulk solid will develop the strength to bridge over the feeder.

Second, conventional feeders have a tendency to withdraw material selectively from the storage bin's discharge outlet. Uneven discharge promotes a first-in, last-out discharge pattern. This is problematic because most cohesive bulk solids, including dewatered tailings, will not reliably discharge in a first-in, last-out discharge pattern.

In summary, the research demonstrated that a reliable storage and feed system handling cohesive bulk solids requires both: a) a storage bin with correct bin geometry; and, b) a feeder that withdraws material evenly from the entire discharge opening of the storage bin.

Keywords: *bulk solids handling, bin plugging, chute plugging, material compaction, uneven discharge, mass flow, funnel flow, discharge feeder, tall bin, dewatered tailings*

1 Introduction

In the late 1970s, Kamengo, (a unit of an independent research institute located on the campus of the University of British Columbia, in Vancouver, Canada) launched a 15-year hands-on research programme to understand and resolve the root causes of bin plugging.

A central focus of the research was to offer solutions to improve the storage and feed of cohesive bulk solids. The first half of the Kamengo team's research programme focused on the design of storage bins, and the second half focused on the feeder. The outcomes of the research programme included both a scientifically grounded approach to determining correct storage bin geometry for cohesive materials, as well as the Kamengo Feeder, which was designed to resolve the key shortcomings of conventional feeders. The new processes and technologies that emerged from the research were in response to the three root causes of bin plugging and uneven discharge that were identified through the research programme (Bundalli 1983). The three root causes of bin plugging and uneven discharge are:

1. Poor bin geometry. Bin geometry, including bin shape, bin wall angles, bin wall materials, and bin discharge opening width and length, need to be chosen according to the flow properties of the stored material. If the feeder were removed from the storage bin, the bin should completely empty with only the aid of gravity.
2. Compaction of the stored material by the discharge feeder. The conveying/shearing action of conventional feeders has a tendency to compact material in the bin. This compaction injects strength into the material. As the stored material's shear strength builds-up, the material is able to bridge over wider distances, making it more prone to plugging, the formation of rat-holes, and uneven feed.
3. Uneven discharge of the stored material by the discharge feeder. When the feeder does not discharge material evenly from the full bin opening, it leaves pockets of stagnant material, which compact and gain strength under their own weight. Further, uneven discharge promotes a first-in, last-out discharge pattern. This is problematic because most difficult flowing cohesive bulk solids, including dewatered tailings, will not reliably discharge in a first-in, last-out discharge pattern. To avoid uneven discharge, the feeder must withdraw material evenly from the full discharge opening of the storage bin, and the bin discharge opening should have a width and length that well exceed the distance that the stored material can readily bridge over.

This paper begins with an overview of the research undertaken by the Kamengo team. Included in the discussion is a primer on the theory for translating a material's flow properties into a minimum geometry required for a storage bin to be able to self-empty with only the aid of gravity. Further, the paper discusses in detail the challenges created by conventional feeders, and how their behaviour contributes to plugging and poor discharge. Included in the discussion, is a brief overview of the Kamengo Feeder, whose purpose was to overcome the shortcomings of conventional feeders. To support the reader's understanding of the content presented in the paper, a case study is included in the discussion to demonstrate how the presented concepts were applied to design two tall truck load-out storage bins handling dewatered nickel laterite tailings filter cake. The paper concludes with a summary of the key outcomes of the research programme, including a recommended design process for delivering better storage and feed systems for handling difficult flowing cohesive bulk solids.

2 Kamengo Research Programme: part 1 – bin design

Beginning in the late 1970s, the first phase of the Kamengo team's research focused on determining the minimum geometry required to discharge a range of large particle and cohesive bulk solids from a storage bin with only the aid of gravity. Minimum geometry includes the minimum angle for the storage bin's sloping walls, as well as the minimum discharge opening to avoid plugging. The starting point for the Kamengo team's research was the early work by Dr Andrew Jenike, at the University of Utah in the 1950s and 1960s.

In simple terms, Jenike's theory reduces the design of a storage bin to a series of physics problems. On the one hand you have gravity, which is fixed and the primary force available to discharge a storage bin, and on the other hand, you have the forces working against gravity, including the shear strength of the material.

Good bin design is about ensuring the geometry of the storage bin is such that the required force for a bulk solid to discharge from the bin is less than what gravity can supply. To determine this minimum geometry, Jenike developed a theory and method that uses a bulk material's flow properties to determine the forces working against gravity when the bulk solid is placed in a storage bin.

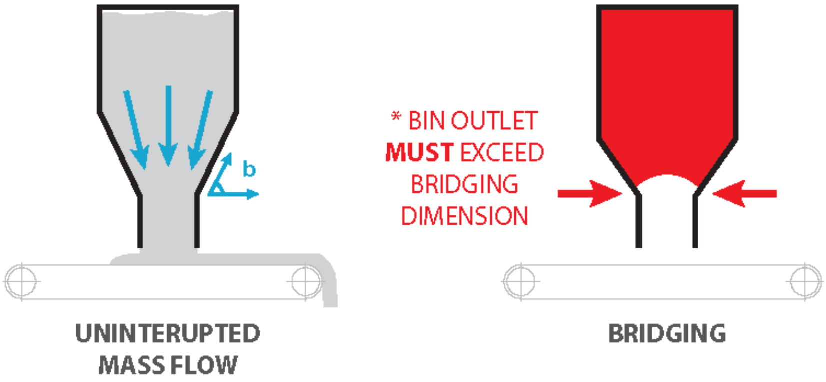
Below is a brief overview of Jenike's theory and prescribed method for determining correct storage bin geometry (Jenike 1964). We encourage those readers interested in learning about Jenike's theory in more detail to review his landmark publication, which is listed as a reference to this paper.

2.1 Primer on Jenike's theory

In summary, Jenike's theory centres on making key decisions on the geometry of the storage bin. However, the starting point of the decision-making process is choosing the desired pattern in which material flows within the storage bin. There are two flow patterns to choose from: mass flow and funnel flow.

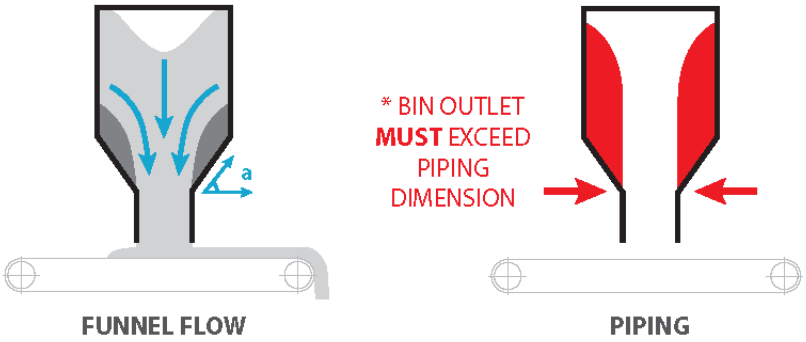
Mass flow is a first-in, first-out flow pattern. With mass flow, all the stored material in a storage bin comes down together as a single mass. Further, with mass flow, the bulk material preferentially slides along the sloping walls of the storage bin (Figure 1a).

The alternative to mass flow is funnel flow. Funnel flow is a first-in, last-out flow pattern. In contrast to mass flow, the stored material funnels through itself and sloughs off from the top down. Further, unlike mass flow, material along the walls of the storage bin is stagnant (Figure 2a).



(a) (b)

Figure 1 **(a) Mass flow discharge pattern; (b) Bridging dimension**



(a) (b)

Figure 2 **(a) Funnel flow discharge pattern; (b) Piping dimension**

To achieve mass flow, the sloping walls of the storage bin need to exceed a minimum angle defined from the horizon. If the sloping walls are less steep than the minimum angle, then funnel flow ensues.

There are two primary factors that determine the minimum angle to achieve mass flow:

1. The coefficient of friction between the bulk solid and the sloping walls of the storage bin.
2. The shape of the storage bin.

In summary, there are a variety of bin shapes, including plane flow hoppers and conical hoppers (Figure 3). The minimum angle required for mass flow for a given bulk material varies from shape to shape.

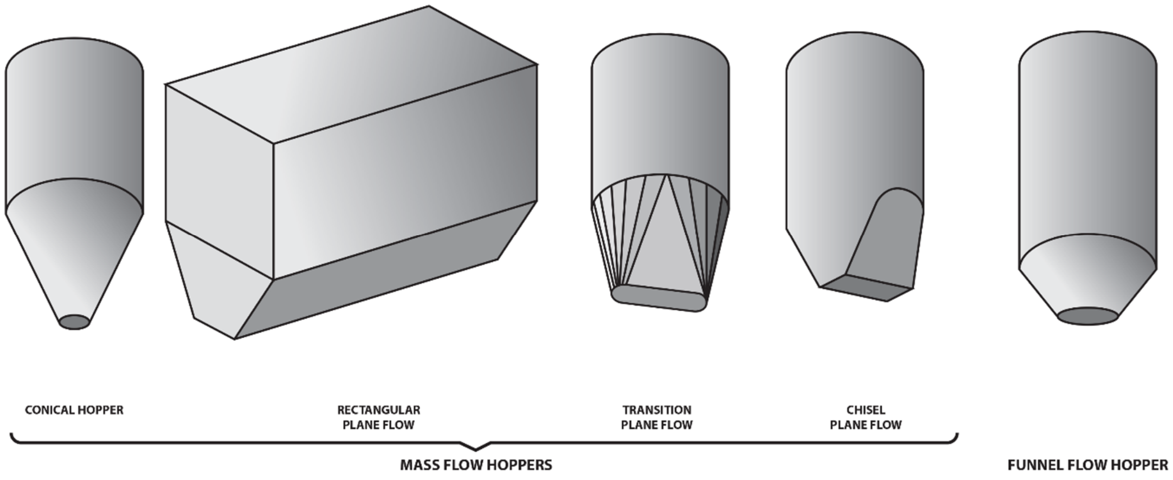


Figure 3 **Bin shapes**

The primary constraint when designing for mass flow is that the effective discharge opening of the storage bin needs to be greater than a bridging dimension (Figure 1b). The bridging dimension is a minimum width and length, or a minimum diameter, depending on whether the storage bin's discharge opening is rectangular or circular. If the effective discharge opening is not greater than the bridging dimension, then gravity will not reliably discharge the storage bin. Instead, the stored material will be susceptible to chronic bridging over the discharge opening.

The primary constraint when designing for funnel flow is that the effective discharge opening of the storage bin needs to be greater than a piping dimension (Figure 2b). The piping dimension is a minimum length, either measured corner to corner of a rectangular discharge opening, or the diameter of a circular discharge opening.

One should note that for a given bulk solid, the piping dimension can be two to ten times larger than the bridging dimension. For many difficult flowing cohesive bulk solids, the piping dimension can be so large that it is impractical to make funnel flow work reliably in a storage bin.

The bridging dimension and the piping dimension, as well as the minimum angle required to achieve mass flow, are derived from material flow characterisation testing, which is a series of bench scale tests developed by Jenike.

2.2 Storage bin design for difficult flowing cohesive bulk solids

Jenike's original research focused on developing theories to design better storage and feed systems handling granules and powders. The Kamengo team was interested in knowing whether Jenike's theories can be used to predict the minimum geometry needed to reliably discharge wet cohesive materials.

The first task for the Kamengo team was to determine the flow properties for a variety of cohesive and large particle bulk solids found in industry. A bulk material's flow properties are determined through a series of bench scale tests, namely the wall friction and shear tests.

To complete the tests, the Kamengo team designed new equipment to perform the flow characterisation testing. New (larger) equipment was required because Jenike's original research focused on granules and powders, and the test equipment he developed were not suited to characterising a wide range of materials including moist or cohesive materials prone to clumping such as dewatered tailings.

Equipment developed by the Kamengo team included a 30 inch ring shear cell, as compared to the standard four inch ring shear cell used by Jenike (Figure 4). The ring shear cell is used to determine the minimum bridging dimension and piping dimension for a given sample.

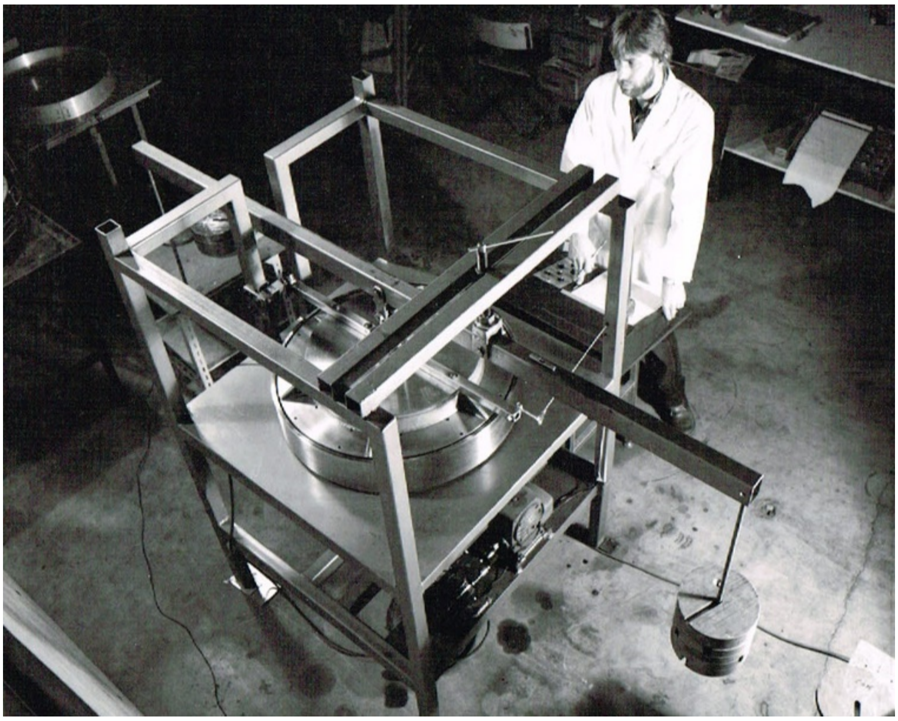


Figure 4 30-inch ring shear cell developed by the Kamengo Team

The Kamengo team also developed a 30 inch wall friction tester (as compared to the standard four inch wall friction tester used by Jenike. The wall friction tester is used to determine the coefficient of friction between the sample bulk solid and various wall materials, including carbon steel, stainless steel, concrete, glass coated steel and plastic linings.

The results of the flow testing showed that when designing for most cohesive bulk solids, mass flow is necessary to avoid flow problems. However, the required angle to achieve mass flow using conventional bin wall materials – including carbon steel and concrete – were very steep and impractical. To design for mass flow, alternative wall materials or liners need to be considered, including plastic liners and glass coated steel.

To prove or disprove the theoretical bin geometries for handling cohesive bulk solids derived using Jenike's theories, the Kamengo team built an 80 cubic-metre plane flow test bin, where the team could change the angle of the sloping walls, change the liner on the sloping walls, and change the width and length of the bin's discharge opening (Figure 5).

Figure 5 Kamengo test storage bin with adjustable sloping walls

The test bin was fitted with a trap door, which was constructed using plywood. With each test, the geometry of the test bin was adjusted according to what the theory identified as necessary to achieve reliable discharge. The test bin was subsequently filled with the test material and the trap door released. The test material would either discharge under gravity or it would hang-up.

The work with the test bin demonstrated that Jenike's theory very much applies to a wide range of cohesive and large particle bulk solids. A key outcome of the research is that it demonstrated that even the most difficult flowing bulk solids will discharge by gravity alone in a converging positive tapered storage bin as long as the geometry of the storage bin and choice of liner on the bin's sloping walls were correctly designed to achieve mass flow.

3 Kamengo Research Programme: part 2 – observing the effects of the feeder

The first phase of the Kamengo research programme focused on the design of the storage bin. The research proved that, using Jenike's theories, one can design a storage bin for a wide range of wet cohesive and sticky bulk solids, where if the feeder were removed, the storage bin would self-empty with only the aid of gravity. The second step of the research programme was to add a feeder to the test bin to meter the discharge of material.

The Kamengo team tested a triple screw feeder and a belt feeder with their test bin (Figure 6). But what occurred surprised the research team. Each time they added a feeder to their test bin, it started suffering from severe plugging.

Figure 6 Triple screw auger mounted to adjustable test bin. The test bin geometry, including sloping wall angle, discharge outlet, and bin liner surfaces were adjusted according to the theory for a given material

To explain the plugging in the test bin, the researchers made two key observations on the effects that the feeders were having on the flow of material in the storage bin.

The research team's first observation was that the feeders were doing two things at once. They were trying to meter material, while conveying material to a single point, and it was the conveying action of the feeder, which was shearing material from the bin that was resulting in compaction (Bundalli 1983)(Figure 7).

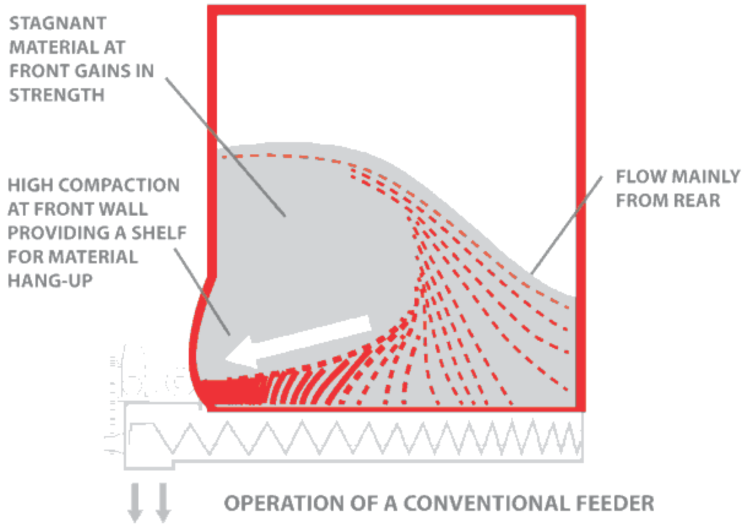


Figure 7 **Shortcomings of conventional feeders**

With a cohesive or large particle bulk solid, the material being sheared out of the storage bin is carrying material above it (either through friction or interlocking) and driving this material forward which, ultimately compacts this material against the bin wall. This compaction was found to have severe consequences. Many difficult flowing cohesive bulk solids, under compaction gain strength very quickly, and consequently, the more shear strength a bulk solid has, the wider the opening it can bridge over. When compacted enough, a bulk solid will develop the strength needed to bridge over the feeder.

The research team's second observation was that the feeders were pulling material preferentially from one area of the bin, usually the rear of the bin. This uneven discharge often left a stagnant pocket of material in the storage bin – most often – at the front of the bin (Figure 7).

Uneven discharge is problematic because when it comes to avoiding bridging or piping in a storage bin, ultimately, it is not the dimensions of the bin discharge outlet that matters, what matters is the effective discharge area, i.e. the area of the discharge outlet from which the feeder is withdrawing material (Bundalli 1983). In other words, regardless of how wide and long a bin discharge outlet is, if the area that the feeder is pulling from is not greater than the bridging dimension or the piping dimension, chronic bridging or piping is likely to occur in the storage bin.

Furthermore, the selective withdrawal of material by the feeders raised a second, more severe consequence. As noted by the earlier flow characterisation work completed by the Kamengo team, the minimum geometry required for many difficult flowing cohesive materials to reliably discharge in a funnel flow pattern are so large that it is impractical to make work in a storage bin. As such, the bin had to be designed to discharge in mass flow. By definition, with mass flow, all the stored material in a storage bin comes down as a single mass during discharge. However, despite the bin geometry being set-up for mass flow, with the unbalanced withdrawal of material by the feeders, the resulting flow pattern in the storage bin was funnel flow.

This proved to be problematic because the discharge opening of the storage bin was designed to be greater than the stored material's much smaller bridging dimension and not its much bigger piping dimension. As a result, it is no surprise, that when paired with the feeders, the test bin began suffering from chronic rat-holing.

3.1 Rethinking the feeder

The negative behaviour of the screw and belt feeders spurred the Kamengo team to rethink the feeder. The team sought to develop a feeder that withdraws material evenly from the full discharge outlet of the storage bin (as opposed to withdrawing material preferentially from one part of the bin discharge outlet). The team also sought to develop a feeder that avoided shearing material from the storage bin which results in material compaction. The team understood that if they could design a storage bin that can self-empty with gravity, then the task for the feeder could be reduced to simply metering the rate at which material discharges from the storage bin. This work led the Kamengo team to develop the Kamengo Feeder.

Following is a case study that highlights the application of Jenike's theory and the use of a Kamengo Feeder to resolve a tall truck load-out bin handling nickel laterite dewatered tailings filter cake. The case study walks through the step-by-step approach Kamengo took to characterise the flow properties of the bulk solid, as well as design and prove a proposed bin geometry and feeder design.

4 Case study: tall bin handling dewatered tailings

In 2019, a nickel laterite mine located in the South Pacific sought a solution to meter dewatered tailings filter cake (Figure 8) into trucks. The design challenge was to fill a 40 tonne truck at 1,600 tph via a consistent, metered discharge from tall truck load-out bins.

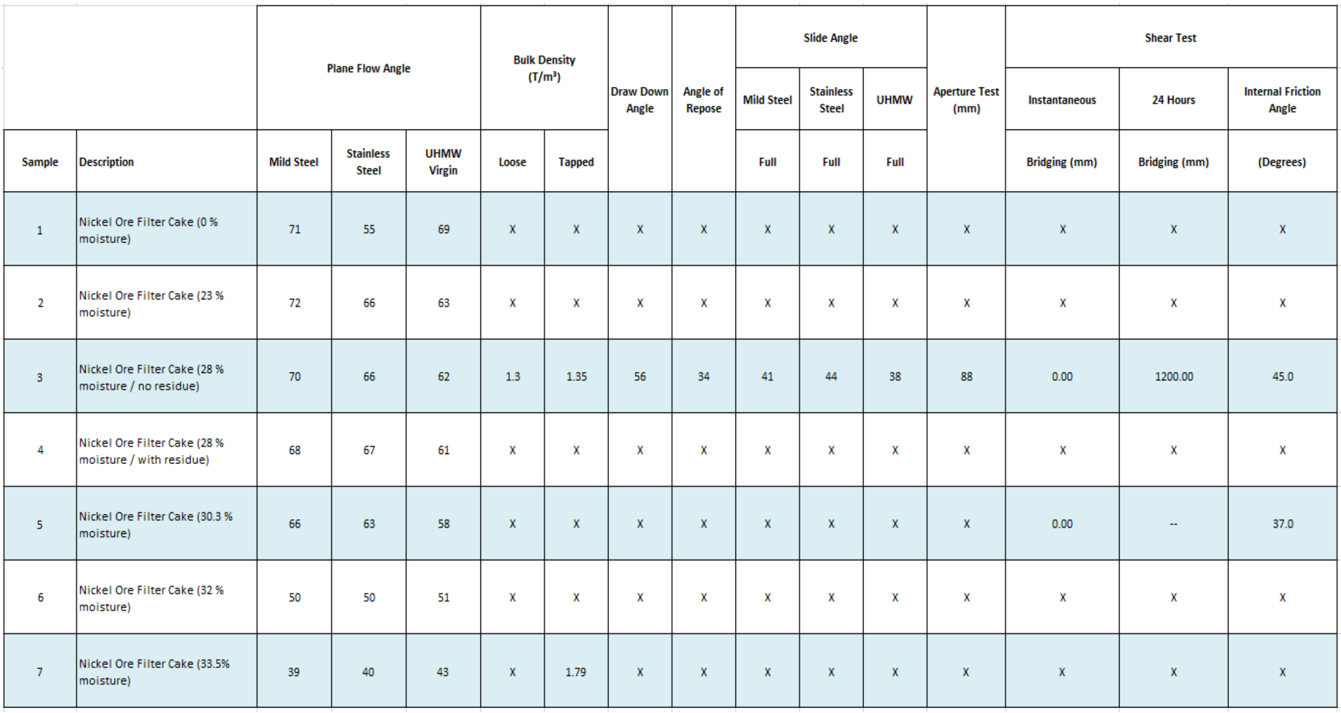
The bulk solid is a wet, muddy filter cake. As such, Kamengo knew that for the truck load-out bins to be reliable, it was important that the design team follow a deliberate design process. The design process was constructed around the six key design decisions that the Kamengo research programme showed are critical to the design of a reliable storage and feed system. These decisions are:

1. Flow pattern. What flow pattern is appropriate for the material and the application? Will funnel flow work or do the material's flow properties require one to design for mass flow? Or does the application require one to combine mass flow and funnel flow, also called expanded flow?
2. Bin shape. What bin shape is appropriate for the material? Are the geometric constraints for a conical hopper reasonable? Do the results of the material flow testing suggest that a plane flow bin shape is most appropriate?
3. Discharge outlet. What is the minimum required discharge outlet? What is the bridging dimension for the stored material? What is the piping dimension for the stored material?
4. Angle of sloping walls. What is the minimum angle for mass flow? If one is designing for funnel flow, what is the minimum angle for the storage and feed arrangement to completely self-empty?
5. Bin liner. Is a liner required on the storage bin's sloping walls?
6. Effective discharge area of the feeder. If one is designing for mass flow, by definition, the effective discharge area of the feeder and the opening of the storage bin must be one and the same. If one is designing for funnel flow, the effective discharge area of the feeder must be greater than the bulk solid's piping dimension.

To resolve the above six design parameters, Kamengo's first step was to characterise the flow properties of the bulk solid. Kamengo conducted six tests on six samples of the dewatered tailings. The samples varied by moisture content so that Kamengo could understand how the bulk solid's flow characteristics changed as moisture content changed.

The tests conducted with each sample included: a shear test, a wall friction test, an aperture test, a bulk density test, an angle of repose test, and a slide angle test. A summary of the test results were compiled in the table (Figure 9).

Figure 8 Sample of dewatered tailings filter cake containing a mix of fines and larger particles.



		Plane Flow Angle			Bulk Density (T/m^3)		Draw Down Angle	Angle of Repose	Slide Angle			Aperture Test (mm)	Shear Test		
									Mild Steel	Stainless Steel	UHMW		Instantaneous	24 Hours	Internal Friction Angle
Sample	Description	Mild Steel	Stainless Steel	UHMW Virgin	Loose	Tapped			Full	Full	Full		Bridging (mm)	Bridging (mm)	(Degrees)
1	Nickel Ore Filter Cake (0 % moisture)	71	55	69	X	X	X	X	X	X	X	X	X	X	X
2	Nickel Ore Filter Cake (23 % moisture)	72	66	63	X	X	X	X	X	X	X	X	X	X	X
3	Nickel Ore Filter Cake (28 % moisture / no residue)	70	66	62	1.3	1.35	56	34	41	44	38	88	0.00	1200.00	45.0
4	Nickel Ore Filter Cake (28 % moisture / with residue)	68	67	61	X	X	X	X	X	X	X	X	X	X	X
5	Nickel Ore Filter Cake (30.3 % moisture)	66	63	58	X	X	X	X	X	X	X	X	0.00	--	37.0
6	Nickel Ore Filter Cake (32 % moisture)	50	50	51	X	X	X	X	X	X	X	X	X	X	X
7	Nickel Ore Filter Cake (33.5% moisture)	39	40	43	X	1.79	X	X	X	X	X	X	X	X	X

Figure 9 Final test results summarised

The flow testing showed that the dewatered tailings would not reliably discharge in funnel flow, and that the storage bin needed to be designed to empty in a mass flow, or a first-in, first-out discharge. Further, the testing provided important guidance on the shape of the storage bin, minimum angle of sloping walls, recommended bin wall liner, minimum discharge opening, feeder discharge chute angle, and the behaviour of the feeder.

In summary the flow testing showed that the nickel laterite dewatered tailings filter cake truck load-out bins should be designed:

- As a series of stacked plane flow hopper. This means that each hopper section only converges in one direction at a time, while the other two walls remain vertical in that hopper section.
- With a minimum hopper angle of 70-degrees measured from the horizon, and that the sloping walls are lined with ultra-high molecular weight polyethylene (UHMW).
- With a minimum 1.2 m wide discharge opening (with a minimum length of three times the width). This wide discharge opening is needed to ensure the bulk solid will not bridge over the bin discharge opening.

- With a fully-effective feeder. The above minimum geometry is intended to produce a mass flow or first-in, first-out discharge pattern over the feeder where all the stored material in the storage bin will come down as a single mass. However, for the combined bin and feeder to deliver mass flow, by definition, the feeder must withdraw material evenly from the storage bin's full discharge outlet. In other words, the feeder must be fully-effective.
- With a minimum feeder discharge chute angle of 45°.

In addition to providing detailed guidance on a recommended bin geometry, the results from material flow testing allow one to compare materials that may not look similar but behave in similar ways in a storage bin. This is particularly useful when handling new bulk solids, because it allows one to borrow experience from more common materials, in particular materials that have been handled in industry for decades.

By comparing the flow function of the nickel laterite dewatered tailings filter cake with the flow function of known materials, Kamengo was able to reveal important lessons learned. A material's flow function illustrates the rate at which a bulk solid's unconfined yield stress increases with consolidation. In other words, the function shows how much shear strength the bulk solid has at the outlet of the storage bin as it is put under pressure. The quicker the rate at which the bulk solid gains shear strength, the more difficult flowing is the bulk solid. More importantly, bulk solids with similar flow functions will behave in similar ways in a storage bin.

In comparing the results of the material flow testing of the dewatered nickel laterite tailings, Kamengo found that it behaves similar to wet gypsum. This is a good example of two materials that look very different but will behave very similarly in a storage bin. Further, Kamengo has delivered equipment handling wet gypsum that has been in operation for several decades. As such, there was an opportunity to carry over lessons learned to the design of the storage and feed system handling the dewatered tailings.

Prior to starting detailed design, Kamengo conducted at-scale pilot testing using a large sample of the dewatered tailings. The testing was done in a plane flow storage bin with a 2.1 m long by 0.9 m wide outlet and discharged by a Kamengo Feeder. The storage bin had 70-degree sloping walls lined with UHMW. Further, the geometry of the Kamengo Feeder was the same as was proposed for the full-scale truck load-out system. Included as part of the testing, was allowing the dewatered tailings to sit in the storage bin for 89-hours so that one could observe whether the material would still flow after sitting stagnant for a long period of time. Further, as part of the testing, additional water was added to the sample of dewatered tailings to the point of saturation to simulate what would happen if the bin were loaded with off-spec material.

The value of the at-scale pilot test was to prove both the geometry of the storage bin and the appropriateness of the Kamengo Feeder, and that when combined they will deliver reliable discharge including under upset conditions.

The final design of the truck load-out bins was to stack two plane flow hoppers on top of each other, with each hopper 90-degrees to the other. Shown in Figure 10 the lower hopper converges in the X-Y plane while the second hopper above converges in the Y-Z plane. Above the plane flow hoppers were several stacked vertical sections. The storage bin discharged via a wide and long 1.5 m × 5.5 m rectangular discharge outlet. The wide and long outlet was required to ensure the dewatered tailings, even under upset conditions, would not bridge over the feeder. Below the outlet was a Kamengo Feeder. In total, two truck load storage bins were delivered to site (Figure 10).

Figure 10 Rendering of truck load bins for handling dewatered tailings

The Kamengo Feeder was chosen for several reasons to discharge the truck load-out bins. First, the feeder withdraws material evenly from the full width and length of the storage bin discharge outlet. The storage bin geometry was chosen on the premise that it would discharge in mass flow. Specifically, the discharge outlet was chosen to be greater than the dewatered tailing's smaller bridging dimension, and not its larger piping dimension. By definition for mass flow to occur, the storage bin must be discharged equally from the full width and length of its discharge opening. If material were to be withdrawn unevenly with stagnant pockets of material, a funnel flow discharge would be induced, and chronic rat-holing should be expected.

Second, the Kamengo Feeder is able to meter the discharge of the bulk solid. This is in contrast to a clam shell which generally delivers an all-or-nothing discharge. If one were to inch a clam shell open to try to meter the discharge, one would pinch the opening of the storage bin, and induce funnel flow, resulting in inconsistent discharge.

Third, the Kamengo Feeder discharges over its full length. As a result, the truck does not need to be inched forward as the feeder discharges. Instead, the Kamengo Feeder discharges the stored bulk solid over the length of the truck bed.

5 Conclusion

The research undertaken by the Kamengo team demonstrated that there are three root causes to bin plugging and uneven discharge:

1. Poor bin geometry.
2. Compaction of the stored material by the discharge feeder.
3. Uneven discharge of the stored material.

To address the three root causes of bin plugging and uneven discharge, designers need to adopt a design process that is informed by the stored material's flow properties and correctly applies Jenike's theory. This includes asking key questions, such as:

- What flow pattern is appropriate for the material and the application? Will funnel flow work or do the material's flow properties require one to design for mass flow? The Kamengo research showed that for most difficult flowing cohesive bulk solids, the geometric constraints needed to make funnel flow work are onerous and that mass flow is generally the only reasonable flow pattern to design for.
- What bin shape is appropriate for the material? Are the geometric constraints for a conical hopper reasonable? Do the results of the material flow testing suggest that a plane flow bin shape is most

appropriate? The flow properties of most difficult flowing cohesive bulk solids suggest that it is difficult to achieve reliable discharge for these materials through a cone.

- What is the minimum required discharge outlet? What is the bridging dimension for the stored material? What is the piping dimension for the stored material?
- What is the minimum angle for the sloping wall?
- What is the appropriate material for the sloping wall? Is a liner needed?

In addition, the research demonstrated that it is critical to think strategically about the feeder. The behaviour of conventional feeders can produce severe negative consequences that may lead to chronic plugging. If one is designing for mass flow, by definition, it is critical that the feeder withdraw material evenly from the entire discharge opening of the storage bin. If one is designing for funnel flow, the effective discharge opening must exceed the bulk solid's piping dimension which may be quite large.

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