A Better Understanding of the Tailings Properties Can Potentially Lead to Improved Backfill Economics

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ABSTRACT

As development projects and operating mines drive for efficiencies, both capital and operating cost are often scrutinized. The selection of technically viable and cost effective backfill is an important task for many underground mines. This paper presents the findings of a study for the Twin Metals Minnesota Project that looked at the results of combining a tailings that readily dewaters, with a slow set binder, such as slag cement. The resulting proposed backfill plant design takes on the simplicity reminiscent of a standard hydraulic fill plant yet maintains the performance and operational benefits of a typical paste fill plant. In this case, dewatered tailings from a high rate thickener can be combined with slag cement to achieve unconfined compressive strengths that are similar to paste.

INTRODUCTION

Twin Metals Minnesota LLC (TMM) is currently pursuing the development of an underground mine in north east Minnesota. Situated between the towns of Ely and Babbitt, the proposed project will produce two concentrate products, containing copper, nickel, gold, platinum and palladium.

Early in the project development and engineering stage, TMM decided to use tailings as a backfill material in order to minimize the footprint of the tailings storage facility (TSF) on the surface. Two of the backfilling options considered initially were paste, and hydraulic fill.

Paste is a form of backfill that has the tailings dewatered to a level where they form a non-segregating material that can be pumped with a positive displacement pump. Paste can be produced from tailings with a wide particle size distribution range, but as a rule of thumb require a minimum of 15 wt% of material pass the 20 µm size fraction. This minus 20 µm fraction is believed to retain colloidal water resulting in a solids suspension (e.g., Ahmed et al. 2010; Cincilla et al. 1997). Paste also has the characteristic of producing minimal bleed water after placement. The consistency of paste is measured using an ASTM slump cone, generally ranging from 7 – 10 inches. A typical paste material will have a solids content of about 75 wt% to 85 wt% solids, depending on the nature (specific gravity, particle size distribution, mineralogy, etc.) of the tailings material. Dewatering of the tailings is typically done in two stages to achieve the required solids content; settling followed by filtration. When placed on the surface, paste can be used without binder. In underground applications, binder is added to meet the underground backfilling strength requirements. This may be for a structural fill or in minimal quantities to mitigate the potential for liquefaction.

Hydraulic fill is a backfill material consisting of a de-slimed slurry that exhibits settling behaviour. When tailings are employed as hydraulic fill rather than a natural sand, the tailings generally must first be processed by cyclones in order to remove the clay sized fraction. Permeability is an important parameter with hydraulic fill, because the water must be allowed to drain from the fill matrix to allow for strength development. With hydraulic fill the tailings solids are suspended in water, forming a slurry that can be pumped using centrifugal pumps. A typical hydraulic fill will have a solids content of 65 wt% to 70 wt%. Hydraulic fill will settle in a pipeline if the velocity is not maintained in the turbulent flow regime. After being placed underground, hydraulic fill releases large quantities of water that must be removed from the stope. Hydraulic fill can be placed with or without binder depending on the mining method employed and the fill strength required.

One proposed mining method investigated by TMM only requires low strength (150kPa), non-liquefiable backfill material to fill the mined out stopes because each stope would be independent from another. In this case, the purpose of the backfill is strictly for the disposal of tailings in order to minimize the surface impoundment requirements. Both paste and hydraulic fill would be a suitable backfill for this mining method.

A hydraulic fill plant would be of a simpler design than a paste plant, and would have a lower overall capital expenditure. Paste however has a distinct advantage over hydraulic fill in that it would require less binder to achieve a specific strength compared to an equivalent amount of hydraulic fill. This stems from the lower moisture content in paste which results in a higher cement to water ratio; an indicator of a cementitious material's ultimate strength. Paste will also achieve higher early strengths than hydraulic fill to reduce the risk of liquefaction at an earlier stage.

Test work was performed on TMM tailings in order to generate data to support the design of each option. It was this extensive testwork that gave light to another backfill option; cemented thickened tailings (CTT). While not commonly used, this backfill method utilizes tailings that have gone through a single stage of dewatering using a thickener. Binder is then added to the thickened tailings and it is pumped underground utilizing centrifugal pumps. This method was considered because of the unique physical properties of TMM's tailings which made them amenable to this process. In this case, a standard high rate thickener would be proposed.

The advantage CTT offers over paste backfill and hydraulic fill is a much simpler process which would translate into a lower capital cost. The main disadvantage of CTT is that it has a higher water content when compared to paste, and will require a marginally higher binder content to achieve the same strength.

This paper will look at some of the unique physical properties of TMM's tailings which make them suitable to the CTT application.

TAILINGS TESTING

Representative samples of TMM's tailings were subjected to a regime of testing that would provide the data necessary for designing the tailings backfilling process. The TMM tailings samples were generated by pilot test work. The tailings sample were subjected to numerous tests, the following being some of the key parameters investigated:

- particle size distribution (PSD)
- settling testing
- binder screening
- unconfined compressive strength (UCS) testing

Particle Size Distribution

The PSD of the tailings is an important consideration for the three different backfilling methods. The PSD was determined using mechanical sieving and a Fritsch laser particle size analyzer in accordance with ASTM D4464. Figure 1 shows the PSD for TMM tailings, and tailings from other types of ore bodies including two from gold mines, and three base metal mines. While not a comprehensive comparison of the tailings PSD spectrum, the sample of tailings illustrated Figure 1 shows that the TMM tailings are on the coarser side at the 100 µm minus side. The relative coarseness of TMM tailings is one of the factors which makes it suitable for a CTT application. A coarse material will generally settle and dewater more readily.

From the perspective of paste backfill, TMM tailings are just marginally acceptable for paste making with just approximately 15% passing the 20µm fraction. The other tailings samples shown on Figure 1 would be suitable for this application with sufficient fines in the 20µm minus region. In order to use tailings as hydraulic fill, they would first need to be cyclone processed in order to remove the clay size fraction. The cycloning of tailings for hydraulic fill must balance the requirement of removing enough slimes in order to produce a fill that is sufficiently permeable versus having enough material remaining in the underflow to meet the backfilling quantity requirements. Since hydraulic fill is accompanied by relatively large quantities of water, the fill itself must be permeable enough to allow the carrier water to drain through it, then out of drainage features designed into the stope. In the case of TMM's tailings, permeability in the lower range of what is acceptable was maintained in order to maximize the quantity of tailings sent underground.

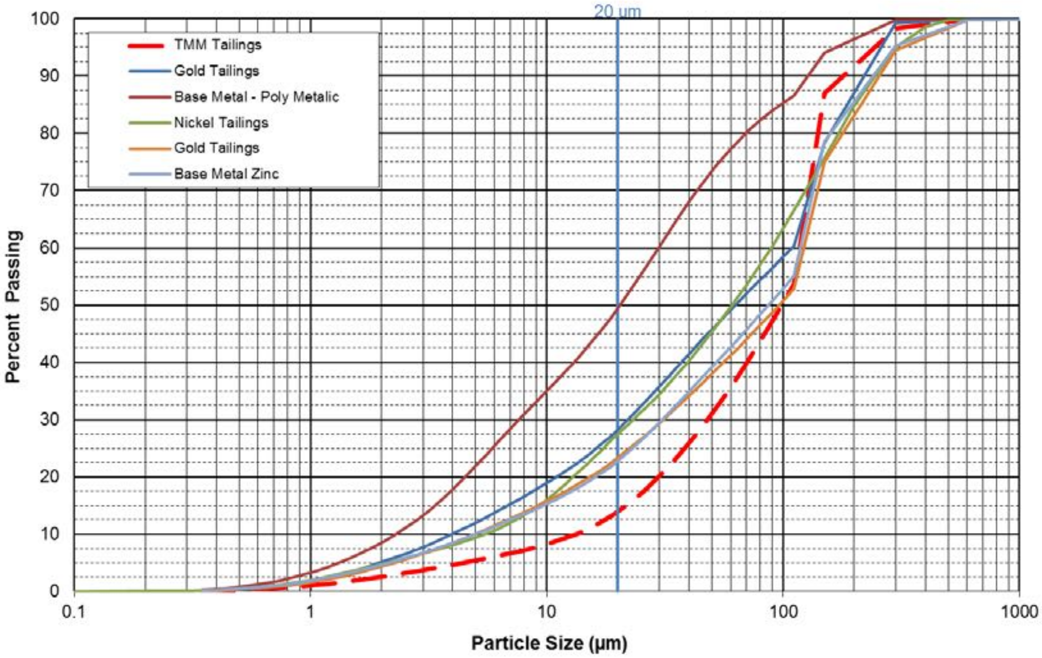

Figure 1. Particle size distribution of various tailings from different ore bodies

Settling Testing

TMM tailings were tested to examine its settling characteristics. The first stage of testing consists of the assessment of various types of synthetic flocculants which are used to form agglomerates of tailings particles and flocculant. Once the most suitable flocculant is selected, the dosage and tailings feed concentration are optimized, by varying these parameters and determining their effect on settling rate, underflow density, and overflow clarity.

The results of sedimentation testing show that TMM tailings settled well. Starting from an optimized feed dosage of around 10 wt% solids, the tailings were settling to 73 wt% solids in around the 4 hour mark. TMM tailings have a specific gravity of around 3.00, which is relatively high, and when combined with the coarser PSD as seen in Figure 1, result in a material that is ideal for thickening. Vendor testing confirmed these results and recommend the use of a high rate thickener for this application. Typical retention times for this type of thickener are under 6 hours. Underflow densities of this concentration are usually achieved using high compression or deep cone thickeners with retention times in the region of 12 to 24 hours. This ability to readily dewater would be one of the factors which makes TMM tailings applicable to CTT.

Binder Selection and Optimization

Extensive laboratory testing was performed investigating binder types, binder blends, and binder addition quantities to be used in the backfill material. In most backfill plants, the binder consumption is the largest operating expense. Even a minor reduction in the binder content of a backfill recipe can be a significant saving over the life of mine.

The mineralogy of tailing from different mines and ore bodies can react to produce varying results with binders. Normal Portland cement (NPC), the most commonly used binder in the construction industry does not always provide the best result for use with tailings. As well as NPC, TMM tailings were also tested with other binders like fly ash (FA), and blast furnace slag (BFS).

Samples were cast into cylinders and allowed to cure for specific periods, most typically 7, 14 and 28 days. After being cured to the prescribed time period, the cylinders were removed from their molds, and compressed to failure in a load frame, resulting in an unconfined compressive strength measurement of the fill. This provided a relative means of evaluating the variables under consideration.

Binder types tested with the TMM tailings sample were:

- 100% NPC
- 50% NPC / 50% FA
- 70% NPC / 30% FA
- 80% BFS / 20% NPC
- 90% BFS / 10% NPC

Fly ash and blast furnace slag are industrial by products of coal burning and steel making respectively, and have pozzolanic properties. When normal Portland cement reacts with water, it produces a hydrated calcium silicate (CSH) and lime (calcium hydroxide). The hydrated silicate provides strength, excess lime from the reaction acts as a filler. Both blast furnace slag and fly ash react with the byproduct lime in the cement reaction to produce additional CSH, often resulting in higher ultimate strengths than in recipes containing NPC alone.

Cement produced in the construction industry uses large quantities of standardized materials like NPC (over 20wt%), sand, and coarse aggregates. When supplemental cementitious material like FA or BFS is added, the reactions are fairly predictable. When FA or BFS are combined with small quantities of NPC and tailings, the reactions vary depending on the cement content and the specific minerology of the tailings sample. The results are not predictable and must be tested to assess the effectiveness of the supplemental cementitious material. In the case of TMM tailings for example, the use of FA did not provide any beneficial results in terms of strength gain of the cured fill when compared to just NPC. When TMM tailings were combined with BFS, and in particular 90% BFS / 10% NPC blend; the results were very favorable. Initial testing was undertaken with 7" slump tailings (79% solids), consistent with a typical paste material. Figure 2, presents the results of the 7" slump paste test work with NPC and BFS binders. A comparison between the 90% BFS / 10% NPC binder (solid line) and the straight NPC binder (dashed line) tests show that significantly higher strength is achieved with BFS binder.

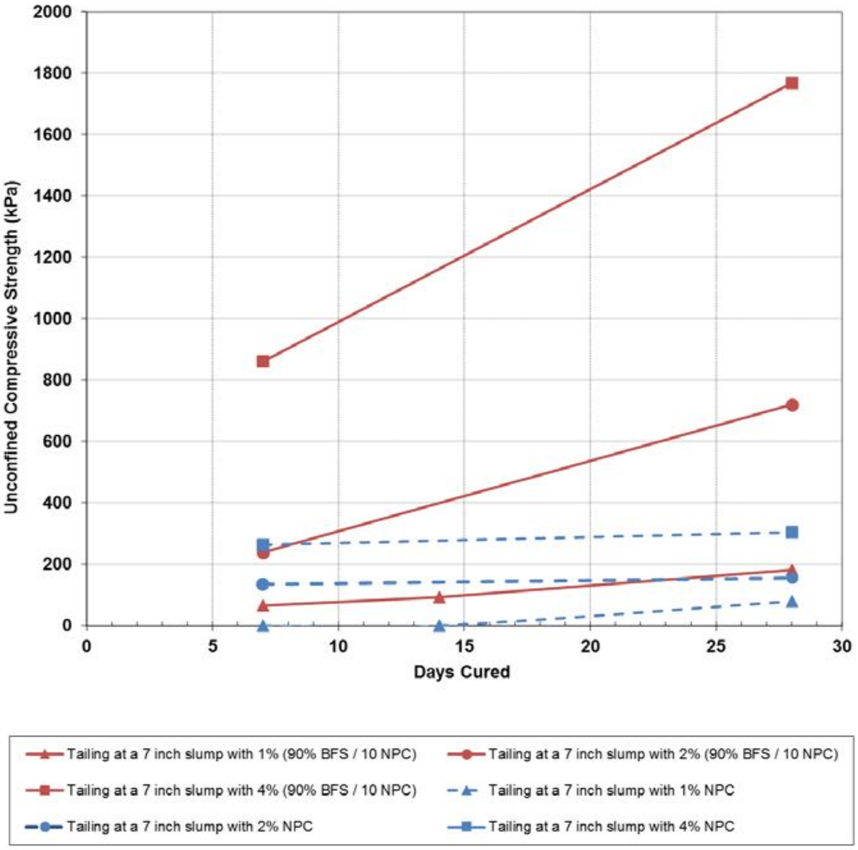

Figure 2. Unconfined compressive strengths for two different binders at varying concentrations for a 7-inch slump paste blend

In order for mill tailings to reach a paste consistency, two stages of dewatering and one stage of repulping are required. TMM tailings were thickened to 73 wt% solids and filtered (vacuum disk) to 83% solids, and then repulped to a paste consistency material. Based on the favorable results obtained using 90% BFS / 10% NPC, and a continued desire to simplify the backfill process, a second round of testwork was undertaken, with the goal of determining the material strength that could be achieved with the addition of BFS binder directly to the thickened tailings. The results can be seen in Figure 3.

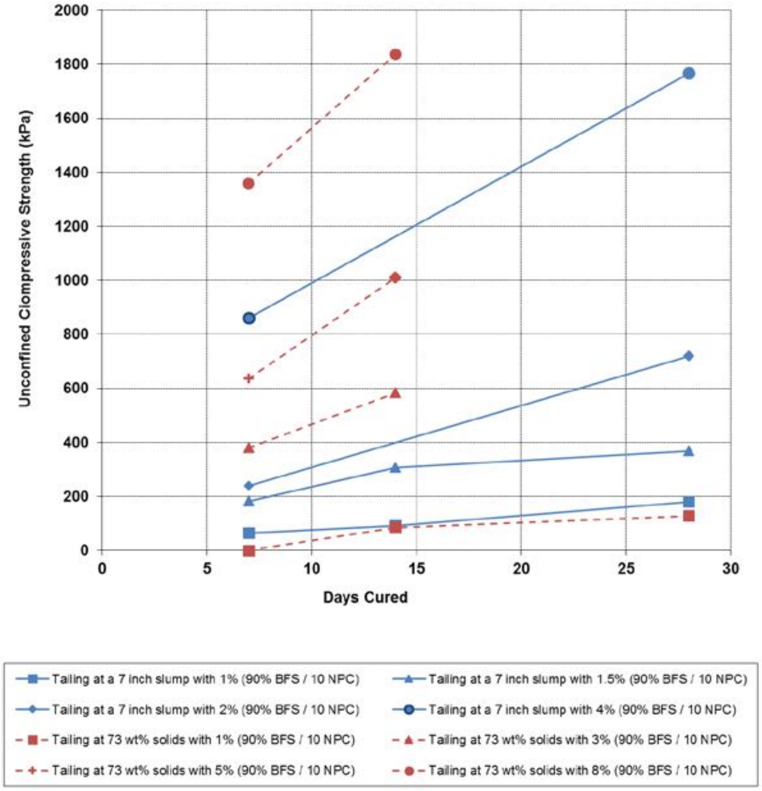

Figure 3. Comparison of tailings with 90% BFS / 10% normal Portland cement at a 7-inch slump and 73 wt% solids

The results were better than expected. Binder contents on tested samples only overlap at 1 wt%; at this value there is only a marginal decrease in strength, in the 10 – 20% range at the 28 day break mark. Although the 7-inch slump paste produces a higher strength for a given binder content (when comparing interpolated results) the data clearly shows that the thickened tailings when combined with modest amounts of 90% BFS / 10% NPC binder does yield UCS values suitable for typical backfill strengths.

It is postulated that the higher than expected strengths obtained with CTT are attributed to the high sedimentation rate of the TMM tailings. Blast furnace slag is typically known to have a delayed onset of strength during curing. During the first few days after placement, it is believed that TMM tailings, which have a high settling rate, are continuing to consolidate from the initial 73 wt% solids, to a higher solids content. The slow onset binder reaction would allow settling to continue after placement.

Simulated Stope Columns

While the UCS results for CTT demonstrated that it could be a viable backfill option, additional data was required to better understand the secondary settling process that was occurring, and how the strength of the backfill material will be affected if the bleed water from the secondary settling were not allowed to drain freely away from the backfill. Standard UCS cylinders have porous openings at the bottom of the casting cylinders that allow the water in the fill to drain out.

A test was devised that would have long cylinders filled with CTT, with no drainage features provided at the bottom. This experiment would mimic the conditions that would occur in large stopes filled with CTT, which may not always have ideal drainage. The simulated stope columns were constructed from 4-inch PVC pipe with the bottom end sealed off. The columns were 7 feet in length; the column height was limited by the ceiling in the laboratory facility.

Three different test columns would be poured with different test parameters, as described in Table 1. Columns 1 and 3 would be filled in one continuous lift, or pour. Column 2 would be filled in three separate lifts, each spaced one day apart. All three columns were filled with a 73 wt% mixture of tailings and the appropriate amount of binder.

Table 1. Simulated stope column test parameters

Column Number	Binder Content (wt%)	Binder	Lifts
1	1	90/10 slag cement	1
2	1	90/10 slag cement	3
3	2	90/10 slag cement	1

Each lift on the simulated stope column would have three 4 x 8-inch reference UCS cylinders cast from the same backfill mix. The stope columns and reference cylinder would be cured in a humidity chamber for 28 days. The columns were then cut with a concrete saw into four equal segment (columns 1 and 3). Attempts were made to cut 4x8-inch sized cylinders from each column section. For column 2, since the lifts were each poured a day apart, the sections would be cut off a day apart allowing each lift to cure for 28 days.

The reference cylinders and the sections cut from the stope columns were compressed to failure on a load frame, with the peak UCS measured at the point of failure. Each broken cylinder was then placed in an oven and dried in order to obtain the moisture content of the respective samples. The result can be seen in Table 2, Table 3, and Table 4 for the three different tests performed.

Table 2. Test result column #1, for a single lift with 1% binder and comparison to cast reference cylinder

Cylinder Description	Measure Solids Content (wt%)	UCS (kPa)
Top Section	73.7	87
Top Middle Section	77.5	95
Bottom Middle Section	77.8	99
Bottom Section	79.1	117
Reference Cylinder	79.8	149

Table 3. Test result column #3, for a single lift with 2% binder and comparison to cast reference cylinder

Cylinder Description	Measure Solids Content (wt%)	UCS (kPa)
Top Section	75.0%	354
Top Middle Section	77.4%	406
Bottom Middle Section	77.4%	395
Bottom Section	77.9%	411
Reference Cylinder	79.0%	524

Table 4. Test results column #2, for 3 lifts with 1% binder and comparison to cast reference cylinders

Cylinder Description	Measure Solids Content (wt%)	UCS (kPa)
Top Section (Lift 3)	77.1%	110
Lift 3 reference Cylinder	79.1%	137
Middle Section (Lift 2)	76.9%	97
Lift 2 Reference Cylinder	79.1%	127
Bottom Section (Lift 1)	78.4%	133
Lift 1Reference Cylinder	79.1%	116

For column #1, poured in a single lift with 1% binder, there is an increasing amount of moisture in the fill as you move up the column. This is not an unexpected result since the weight of material above consolidates the material below with increasing pressure lower in the column.

The top of the fill in the PVC pipe had a small pool of water sitting on top from secondary settling. The volume of this water was measured; it represented approximately 19% of the available water. It should also be noted that some of the water in the fill is being consumed by the cement hydration reaction.

The moisture in the simulated stope column did not reach the level of dewatering of the reference cylinder. This may be attributed to the UCS cylinder having additional drainage from the bottom of the cylinders. UCS results paralleled the results of the moisture with higher strengths observed at the bottom of the column, and progressively lower with the sections above. The large column was not able to achieve the same strength as the reference cylinder.

The results for column #3, poured with a single lift and 2% binder produced similar results as column #1, with increasing solids content and strength lower in the column. It was noted during the testing that the top layer of columns 1 and 3 had slimes present, more so than the layers below. This is evidence of segregation of the material after placement and is often seen with UCS cylinders cast with hydraulic fill. This could account for why the top layer of the column had the lower strength. UCS cylinders will often fail near an observed slime layer.

The results for column #2, poured with three lifts, and 1% binder, has less pronounced strength gain in the bottom layer than the two layers above, with more consistent results for all three layers. This suggests that the compressive force of the material above has more effect early on (within 24 hours of placement), than at later stages. As with the other tests, each layer in the column was not able to achieve the strength of the reference cylinder for that layer.

The water to binder ratio is used in the concrete industry as a relative means of gauging a mix design's strength and is calculated by dividing the mass fraction of water by the mass fraction of binder. The amount of water in a recipe has a significant influence on a recipe's ultimate strength, with higher strengths achieved at lower water to binder ratios. The water to binder ratio was calculated for the simulated stope cylinders and their reference cylinders and plotted against the 28 day strengths, as seen in Figure 4. Note that the water content used in this calculation is the moisture value measured in the cylinders at their 28 day break.

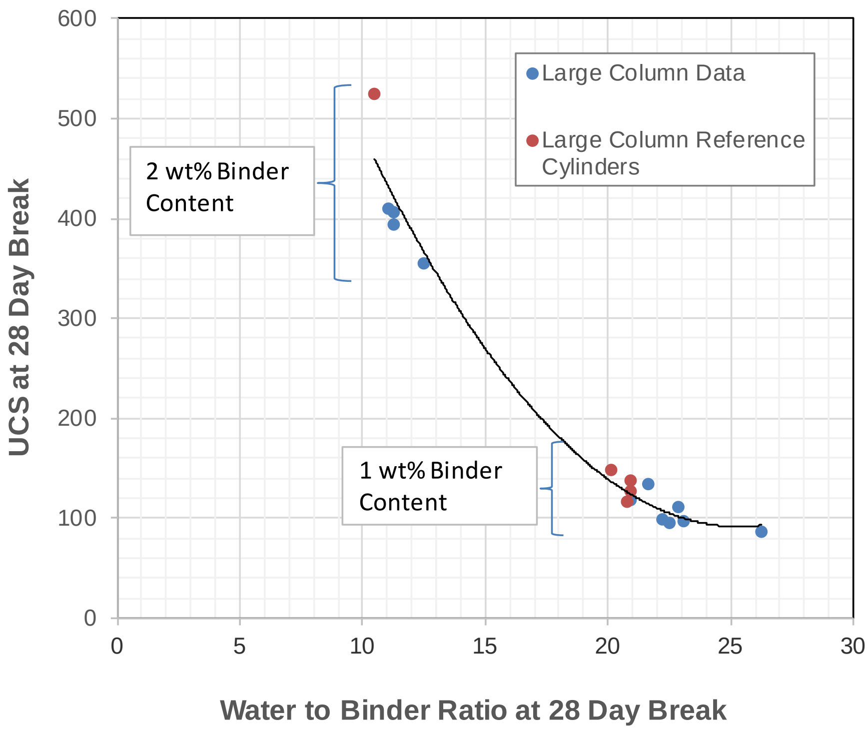

Figure 4. Water to binder ratio vs. UCS at 28 days

The trend line in Figure 4 appears to follow a polynomial relationship which is often seen in concrete mixes. This graph serves to illustrate that a lower water to binder ratio also has a pronounced affect in backfill mixes designs, even at a relatively low binder content of 1 – 2 wt%.

DISCUSSION

CTT Tailings Characteristics

TMM tailings are well suited to CTT application due to their unique physical characteristics. The combined effect of the tailings being relatively coarse, and having a high specific gravity of 3.0, allows the tailing to dewater very efficiently in a thickener, and produce a high solids concentration of 73 wt% solids underflow.

The UCS results for the simulated stope columns and the reference cylinders show that the tailings will continue to go through secondary settling after placement, even when suitable drainage is not provided. TMM tailings also have an affinity to 90/10 slag cement which is known to have a slower onset of strength. This allows the secondary settling and dewatering to continue after placement. In TMM's case the same results would not likely be attained with just NPC alone.

Two other mines that operate using CTT are the Lisheen mine in Ireland and the El Toqui mine in Chile (e.g. Fehrsen et al. 2006; Gridley et al. 2013). Both of these mines are base metal mines and produce zinc and lead concentrates, with El Toqui producing some byproduct gold and silver as well. Zinc tailings are known to have high specific gravities (3.0 and higher), and typically employ a coarser grind. Lisheen uses BFS and NPC in various proportions in their mix designs. El Toqui however only uses NPC.

CTT Application in Stopes

The 28 day UCS results for the simulated stope columns were in all but one case lower than the reference cylinders for the same mix. The higher strengths for the cast reference cylinders is believe to be attributed to the additional drainage being provided at the bottom of these cylinders, thus providing two paths for dewatering (up and down). These results serve as an example for providing proper drainage within a stope in a CTT applications. If proper drainage is not provided, the benefits of a CTT may be negated by not achieving the design strength of the fill material. Since CTT is a segregating material, slimes will likely settle out on the top of the fill, and will form at weaker strengths than the material below. In the case of TMM's backfilling target of producing non-liquefiable fill in non-entry stopes, this would not be an issue. In other mining methods, a layer of slimes on top of the CTT may be of concern if traffic-ability is required.

CTT Relative Economic Advantages over Hydraulic Fill and Paste

When comparing CTT to cemented hydraulic fill, CTT would have an operational advantage in the form of a lower operating cost resulting in lower binder consumption. The higher water to binder ratio encountered with hydraulic fill would require more binder to achieve the same strength as a CTT mix design. Additionally, the slimes resulting from the cyclone processing for hydraulic fill must be managed for surface disposal and if any form of dewatering is required, this would be more demanding compared to whole tailings.

A typical paste plant has a vacuum disc filter for its second stage of dewatering. From there, filter cake discharges into a paste mixer where binder is added, and the final slump or moisture content adjustment is made. For TMM's case, the paste mix would be pumped underground using a positive displacement pump. For the proposed CTT plant, both the vacuum filter unit with all of its ancillary equipment and the paddle mixer could be eliminated. The required building to house the CTT plant would also be smaller. A positive displacement pump to deliver the backfill mix to the underground would still be required in this case. When priced out for TMM's specific site and process requirements, the capital cost saving for the CTT plant was over 50% when compared to a same capacity paste plant. The CTT plant will have a higher overall binder consumption compared to an equivalent sized paste plant. At the same time, the power consumption is 30 % less by comparison.

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