

Use of Cemented Paste Backfill Boreholes for Concrete and Shotcrete Delivery

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ABSTRACT

Deeper underground mining is becoming more prevalent throughout the world. With this comes the fact that the installation of infrastructure to deliver bulk materials in support of mining can add significantly to the overall cost of a project. To this end, the multi-purposing of required infrastructure can lead to significant cost savings during a mine's development, and operation. The use of cemented paste backfill dipped boreholes for delivery of concrete and shotcrete underground is one possible way to bring about economical and efficiency benefits to a project. This paper presents some of the design and technical consideration that went into such an evaluation as part of feasibility studies undertaken by Glencore's Sudbury Integrated Nickel Operations (Sudbury INO) for the Onaping Depth (OD) Project.

INTRODUCTION

Historically, concrete and shotcrete are delivered underground via shaft haulage, pipes or vertical boreholes, if no access ramp from surface is available. Using final, dipped paste backfill boreholes for concrete and shotcrete delivery during project development presents a significant overall project cost reduction if potential risks can be minimized or eliminated. This paper discusses some of the potential technical risks and challenges in using dipped boreholes for concrete/shotcrete delivery; such as segregation, flowability, and health and safety in the context of the OD Project which is currently at a Feasibility Level assessment. The Sudbury (INO) OD nickel/copper deposit is over 2.5 kilometers (km) below the surface near two past producers, the Craig Mine and the Onaping Mine (Figure 1). Sudbury (INO) activities in the Sudbury Basin include exploration, Fraser Mine, Nickel Rim South Mine, Strathcona Mill and Sudbury Smelter. The company has been mining nickel-copper ores in the Sudbury area of northern Ontario, Canada since 1928. It currently employs approximately 1,300 permanent employees.

BACKGROUND

Golder Associates Ltd (Golder) was retained by Glencore's Sudbury Integrated Nickel Operations (Sudbury INO) to develop a feasibility level design of a mine backfill system in support of the ongoing feasibility study on the OD Project. The processing of the ore from the 3,315 tonnes per day (tpd) underground mine will be performed at the Strathcona Mill and will possibly be supplemented with additional ore streams from other mines. A partial tailings stream from the Strathcona Mill will be extracted and used to produce cemented paste backfill (CPF) at the paste backfill plant (PBP) located at the Mill. The CPF will be delivered via ready-mix trucks to a remote borehole building (RBB) located at

the Craig Mine where it will be discharged down a series of boreholes and pipes into stopes at the Onaping Depth Mine.

During the Onaping Depth Project feasibility study, Sudbury INO determined there could be a potential time-related bottleneck in the delivery of material containers via the existing Craig Mine shaft infrastructure, especially during the internal shaft sinking phase. Since there is no connected access ramp from surface to the underground workings, a large number of trips would be required via the existing Craig cage to bring the required amount of concrete and shotcrete underground, particularly to the Onaping Depth winze location.

Possible options were formulated providing different alternatives for the delivery of concrete/shotcrete underground. Due to the depth of the mine (Figure 2: Craig shaft is 1495m deep, with Onaping Depth winze beginning at 1200m), all options include some form of intermediate material handling in the haulage drift connecting the Craig shaft to the internal shaft on the 1200 Level before the material can be delivered to OD. These options are presented in Table 1.



Figure 1. Location of Glencore's Onaping Depth Project

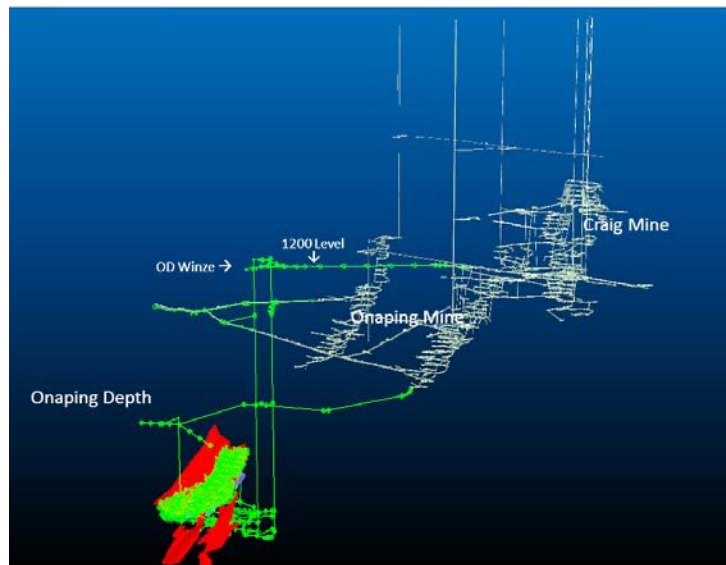


Figure 2. Isometric view – Craig Mine, Onaping Mine and OD

Table 1. Concrete/shotcrete delivery options

	Option 1	Option 2	Option 3*	Option 4
Type of Material on Surface	Dry	Wet		Dry
Transport Method from Surface to Intermediate 1200 Level	Cage	Vertical Borehole		Cage
Size of Cassettes	Existing 5 m ³	Not applicable		New 9 m ³
Type of Material Transported on Intermediate Level	Dry	Wet		
Transport from Intermediate Level to Point of Use (bottom of mine)	Cage	Vertical Borehole		
Location of Batch Mixing Plant	At point of use	On surface	On Intermediate Level	

*Note: The only difference between Option 2 and 3 is where the borehole is located on Surface. Option 2 is located above Craig Mine while Option 3 is located above Onaping Depth Mine.

Option 1 was eliminated due to the demand on the cage at the Craig Shaft and the 1200 Level haulage drift to reach the internal shaft, the limitation on the existing cassette sizes, and the potential bottleneck situation.

Option 3 was eliminated due to environmental permitting requirements to build a surface borehole station above the Onaping Depth mine for pouring concrete and shotcrete underground to an intermediate level. Option 2 was eliminated due to the cost of boreholes from surface to an intermediate level. Option 4 was recommended although it still places a high demand on the Craig cage and required the excavation of an area underground for locating the Batch Mixing Plant, in addition to the purchase of larger capacity cassettes to optimize cage usage.

Option 2 would be preferable as it removes the demand on the cage at the Craig Shaft and eliminates the need to locate a mixing plant on an intermediate level. However the cost of the boreholes and extra surface infrastructure remained too significant. If the dipped backfill boreholes, which are required to provide backfill once the mine enters full production could also be utilized at the pre-production stage, it would reduce cost. This resulted in Golder being asked to evaluate further options:

Table 2. Additional concrete/shotcrete delivery options

	Option 5	Option 6
Type of Material on Surface	Dry	Wet
Transport Methods from Surface to Intermediate Level	CPF Dipped Borehole	CPF Dipped Borehole
Type of Material Transported on Intermediate Level	Wet	
Transport from Intermediate Level to Point of Use (bottom of mine)	Vertical Borehole	
Location of Batch Mixing Plant	On surface	

EVALUATION OF BOTH DRY AND WET CONCRETE/SHOTCRETE THROUGH A DIPPED BOREHOLE

The initial comparison between Option 5 and 6 was based on precedence of delivering concrete/shotcrete through dipped boreholes. Transportation of wet concrete/shotcrete is very similar

to the transport of paste aggregate fill (PAF) which is currently being used in a few operating mines. Transportation of dry granular materials has been achieved using a pneumatic transport system to ensure that no particles segregate or remain in the borehole (for a given particle size range). Golder is not aware of a pneumatic transport for particles in the size range of concrete, making the dry concrete the least preferred option.

The following parameters were examined when evaluating the options:

- Wear on borehole;
- Possibility of segregation;
- Infrastructure requirements (both on surface and underground);
- Efficiency of producing the final product;
- Admixtures required;
- Blockage potential; and
- Ease of transport.

The least amount of wear on the borehole is by using a dry concrete/shotcrete, with the shotcrete having the most negligible amount of wear due to the smaller particle size compared with concrete. Dry concrete has the largest chance of segregation and blockage potential due to the large particles.

Both options have surface infrastructure requirements – either a mixing plant on surface or a pneumatic transport system and borehole station. The wet mix, once prepared reduces the infrastructure requirements underground as it discharges directly into transmixer vessels to be delivered to the point of use while the dry mix requires a mixing station and a dust collection system, potentially with increased ventilation for high dust loading. While the lack of infrastructure underground is an advantage for the wet option, it also means that admixtures will be required to ensure that the concrete/shotcrete does not set before arriving at its destination. With the dry option, the concrete/shotcrete is prepared closer to the point of use reducing the amount of admixtures needed. Having a ready-mix plant on surface and delivery through a borehole is well-known and more efficient than an underground plant. In this instance, the delivery of a mix from a ready-mix truck to a borehole is also required for paste backfill and therefore will eventually have to be built as part of the overall mine plan and therefore is not an additional expense.

One of the largest disadvantages of the dry option for concrete/shotcrete is that if there was any water infiltration in the borehole, it would hamper the delivery underground and build up in the borehole with the potential to create a blockage. Due to preference that the borehole not be fully cased (if not required), this is a major disadvantage.

The final recommendation was Option 6—wet concrete/shotcrete due to the following reasons:

- Potential infiltration of water through the borehole (if not cased);
- Precedence that it has been done and is currently being done in a similar manner in industry;
- Lack of underground excavation/infrastructure required by being mixed on surface;
- Reduced risk of segregation compared with dry concrete; and
- More efficient mixing on surface.

The Option 6 concept is illustrated in Figure 3. Using wet concrete/shotcrete through a dipped borehole still has its risks and challenges. These are examined in the following sections.

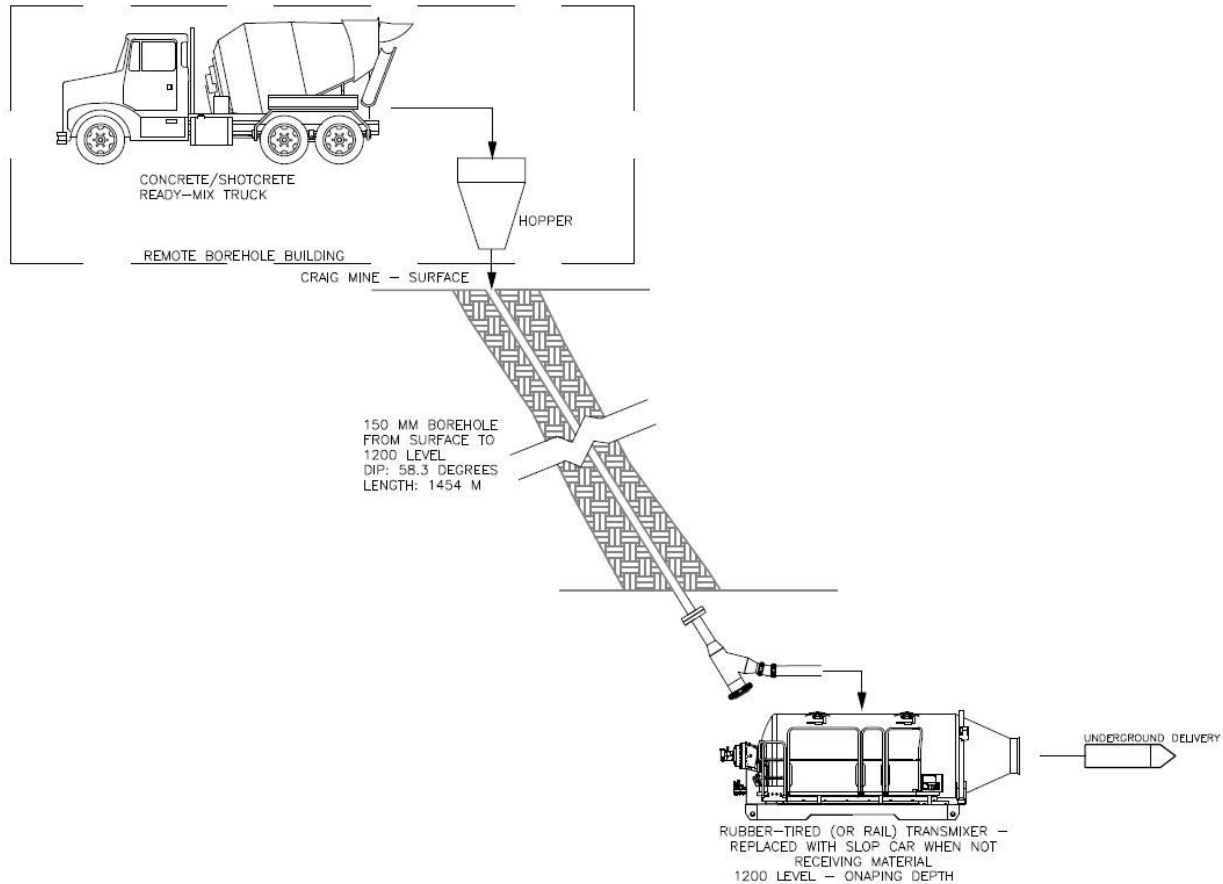


Figure 3. Schematic of option 6 – wet concrete/shotcrete delivery in CPF boreholes

FLOWABILITY THROUGH A DIPPED BOREHOLE

A study was done to determine if an appropriate mix design was possible using typical concrete slump requirements, tonnages required, and possible pressure losses anticipated within the dipped borehole.

Full Flow Condition

The first investigation looked at a full flow condition to determine if it was possible to develop a concrete/shotcrete mix design where the frictional losses generated by the concrete or shotcrete flowing in the borehole could be balanced against the available head to minimize flow velocities and borehole wear.

The static head is calculated by taking the change in elevation between the dump stations at the surface borehole collar and at the required mine level where the shotcrete and concrete will be delivered into a transmixer. This vertical distance, or static head taken from the Golder flow model is 1,237 m. It is then multiplied by the gravitational constant and the slurry density and divided by the actual length of the borehole to calculate the pressure loss to achieve a full flow system in kPa/m.

The slurry densities of concrete and shotcrete were estimated based on the information in Table 3. The concrete recipe is an example of concrete used in shaft sinking applications, whereas the shotcrete recipe is an example of one used for underground excavations. Included in Table 3 is the paste backfill mix recipe to provide a comparison.

Table 3. Typical material properties

	Paste Backfill ⁽¹⁾ (kg/m ³)	Concrete ⁽²⁾ (kg/m ³)	Shotcrete ⁽³⁾ (kg/m ³)
Binder:			
GU Cement (normal Portland)	4.5	150	470
Blast Furnace Slag	40.5	350	-
Silica Fume	-	-	40
Solids:			
Tailings	1753		
Fine Aggregate <10 mm	-	595	1630
Coarse Aggregate < 19 mm	-	1150	-
Fibres	-	-	7
Water	406	180	180
Admixtures:			
Superplasticiser	-	5	1.5
Water Reducer	-	-	2
Accelerator (Point of Use)	-	-	13
Properties of Material:			
Density (t/m ³)	2.204	2.430	2.343
Wt.% Solids	81.6	92.4	91.6
Slump (mm)	175	60	220
Slump (after plasticizer)		> 160	

Notes:

- (1) Paste Backfill Properties
- (2) Auld, F.A. 1989 Conference
- (3) Hoek, Evert. 2007, Shotcrete Support - Adjusted based on email exchange with Andy Wallgren at Fisher Wavy Inc.

The friction loss or pressure gradient is calculated based on the actual borehole distance from surface to the required level taking into account the dip angle of the borehole. Based on a dip angle of 58.3 degrees (dictated by the final duty paste fill requirements) the distance is 1,454 m.

For the system to be balanced, the pipeline pressure loss must equal the static head divided by the borehole length.

$$\text{Pressure Loss (P}_L\text{)} = \Delta H \times g \times SG / L$$

$$P_{L(\text{concrete})} = 1237 \text{ m} \times 9.81 \text{ m/sec}^2 \times 2430 \text{ kg/m}^3 / 1454 \text{ m} = 20.3 \text{ kPa/m}$$

$$P_{L(\text{shotcrete})} = 1237 \text{ m} \times 9.81 \text{ m/sec}^2 \times 2343 \text{ kg/m}^3 / 1454 \text{ m} = 19.6 \text{ kPa/m}$$

Therefore, for the concrete and shotcrete to flow by gravity to the required level using the paste backfill dipped borehole the friction loss must be less than approximately 20 kPa/m. If the pressure loss is greater than this a pump would be required.

Since the pressure loss is a function of the velocity, it is important before moving to the second step, to have an indication of the velocity of the material within the borehole.

Information provided in the Cemented Paste Fill (CPF) Ready-Mix Haulage budgetary quotes indicated that the ready mix truck unloading could vary between 1 to 2 m³/min (60 to 120 m³/hr). Supplemental information provided by a ready-mix supplier indicates unloading rates can reach 3 m³/min, however they note this would be in excess of what boreholes can accept for conventional concrete. They also mentioned that typically boreholes can handle concrete delivery rates between ¾ to 1 m³/min (45 to 60 m³/hr).

The second step is to determine what the friction factor / pressure loss would be for concrete and shotcrete flowing at the velocities determined in the previous section in a 150 mm (6”) borehole. Finding actual pressure loss information for concrete / shotcrete proved to be difficult. Fortunately a graduate student at Sherbrook University carried out a number of flow loops on different types of concrete during completion of a PhD Thesis, CVC (Conventional Vibrating Concrete); SCC (Self-Compacting Concrete) and HWC (High Workability Concrete). Flow loop tests were carried out on 102 mm (4”) and 127 mm (5”) pipelines and the pressure losses were calculated for different concrete flow rates having different slump / slump flow values.

The slump test is typically used to evaluate the ability of concrete to deform under its own weight using the slump (or Abram) cone (ASTM C143). For CVC, the test is executed by casting concrete in three layers and rodding each layer 25 times. For SCC, this test consists of determining the mean diameter of concrete spread on the flat surface underneath the cone at the end of a slump test. For HWC the concrete is inserted in one layer and consolidated by rodding 10 times. For SCC the same procedure was followed with no consolidation required. All values less than 300 mm (11.8”) are slump measurements, whereas values greater than 300 mm (11.8”) are slump flow values that measure the diameter of the material spread on the flat surface underneath the cone.

Using this flow loop data and the Darcy Weisbach equation, the pressure losses in a 150 mm borehole were estimated. The highest and lowest friction loss values provided the range for both the 45 and 60 m³/hr flow rates, as presented in Figure 4, and were utilized to define an envelope of “theoretical” hydraulic grade lines for the concrete mixes tested. The area above the borehole profile would require pumps to overcome the friction losses whereas for the area below the borehole profile would mean the material would flow by gravity. This is principally friction loss dependent. From the available flow loop data it appears that many of the mix designs would be suitable for delivery in a dipped borehole as laid out in the Onaping Depth Project.

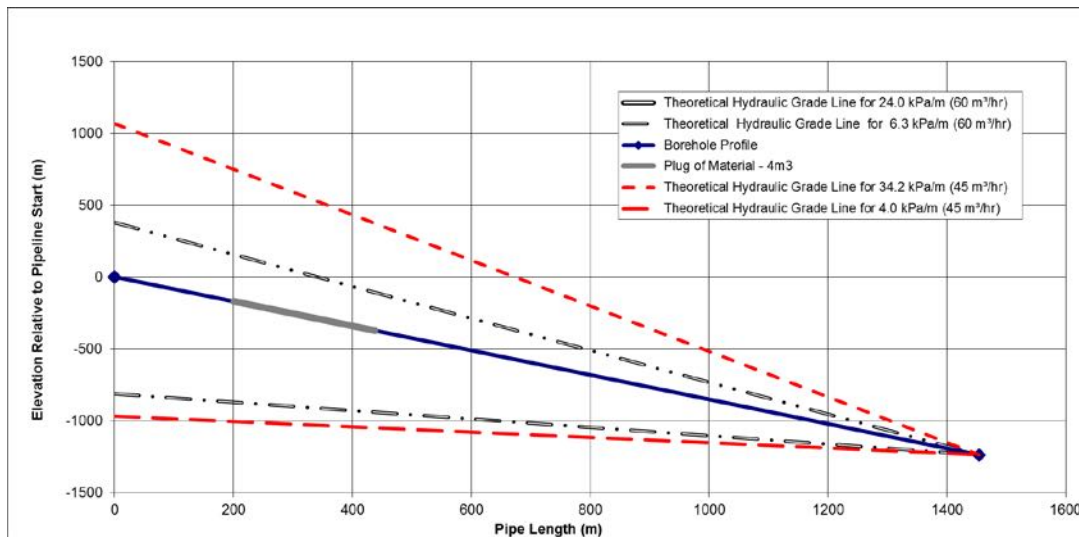


Figure 4. “Theoretical” hydraulic grade lines for 45 and 60 m³/hour

Table 4 provides a comparison of some of the mix designs for different pressure loss values. The mix designs are very similar however they have very different pressure losses. One of the conclusion of the PhD Thesis was that while there is a firm relationship between slump / slump flow (spread) and yield

stress there are no meaningful relationships between slump / slump flow (spread) and viscosity or pressure loss except for the CVC (Conventional Vibrating Concrete).

Table 4. Mix design comparison having different pressure loss values

	SCC5	SCC9	HWC4
	Pressure Loss		
Pressure Loss @ 45 m ³ /hr	7.4 kPa/m	5.2 kPa/m	20.9 kPa/m
Pressure Loss @ 60 m ³ /hr	8.0 kPa/m	7.2 kPa/m	24.0 kPa/m
	Concrete Mixture (kg/m³)		
Binder:			
GU Cement (normal Portland)	400	515	595
Fly Ash Type C	144	-	-
Silica Fume	35	45	52
Solids:			
Sand <10 mm	850	850	803
Aggregate < 10 mm	603	603	642
Aggregate < 20 mm	151	151	161
Water	165	186	154
Admixtures:			
Water Reducer / Viscosity Modifier	10.5	8.15	18.9
	Concrete Mixture Properties		
Density (t/m ³)	2.361	2.358	2.426
Slump (mm)	750	735	580
Strength MPa (days)	66.1 (29)	81.8 (29)	69.4 (29)

Therefore, while admixtures can increase the slump / slump flow (spread) they do not necessarily reduce the pressure loss. Figure 5, which looks at the entire data set in the 2013 Rami Khatib PhD Thesis, clearly shows there is no relationship between slump and pressure loss. As a result, it will be necessary to perform material testing to establish the appropriate concrete and shotcrete mix designs.

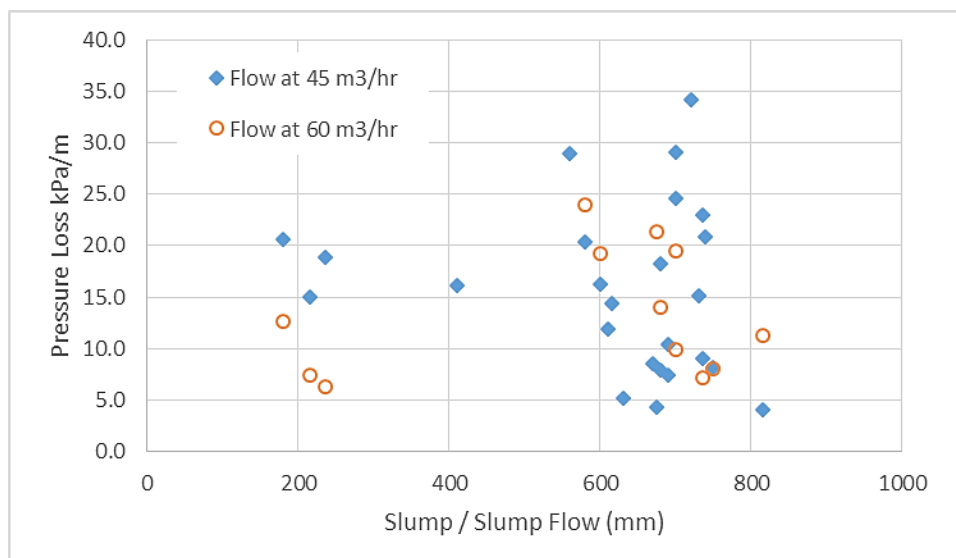


Figure 5. Pressure loss as a function of slump

Slack Flow Condition

The majority of the concrete and shotcrete will be delivered underground in batches and since the borehole is dipped, there is a possibility that slack flow would occur. Under slack flow conditions the concrete / shotcrete could potentially flow with a free surface as if it was in an open channel or launder. This risk is present when the borehole slope (borehole profile) is steeper than the hydraulic grade line. On Figure 1, the borehole profile is steeper than the “theoretical” hydraulic grade lines below it. As discussed in the previous section, this is the condition needed to deliver the concrete and shotcrete underground using gravity. Therefore, when delivering concrete and shotcrete underground in batches, the system will be operating under slack flow conditions.

Under slack flow conditions the concrete / shotcrete will accelerate until it reaches a velocity where the hydraulic gradient equals the borehole slope. The higher the velocity the material achieves the more severe the erosion will be on the bottom surface of the borehole. The highest velocities and erosion will occur in a borehole that is nearly vertical since the material would be free falling.

Shown on Figure 1 is the length within the borehole that a 4 m³ plug would occupy. Based on the slope of the borehole, the material would not have a great distance to go before the material comes in contact with the borehole walls. Therefore, the extremely high velocities that would occur in a vertical borehole under free fall conditions could be significantly reduced. The batch fills approximately 238 m or 16% of the total borehole length. This is a considerable volume that will likely move as a plug (especially since the mix design will be engineered to minimize material segregation) and comes in contact with the entire circumference of the borehole wall. With proper mix design the velocity could therefore be a function of the pressure loss of the material as it moves down the borehole.

To minimize the velocity at which the batch (plug of material) will flow down the borehole it will be important to engineer a mix design that closely matches the pressure head this plug will generate over a portion of the borehole’s length.

$$\text{Pressure Loss (P}_L\text{)} = \Delta H \times g \times SG / L$$

$$P_{L(\text{concrete})} = 202.9 \text{ m (plug height)} \times 9.81 \text{ m/sec}^2 \times 2430 \text{ kg/m}^3 / 237.9 \text{ m (plug length)} = 20.3 \text{ kPa/m}$$

$$P_{L(\text{shotcrete})} = 202.9 \text{ m} \times 9.81 \text{ m/sec}^2 \times 2343 \text{ kg/m}^3 / 237.9 \text{ m} = 19.6 \text{ kPa/m}$$

These values are the same as those calculated for the full flow system. Therefore regardless of the batch size, to minimize the increase in velocity and to minimize wear, it will be necessary to operate the system close to the pipeline profile, however with sufficient leeway to prevent the material from hanging up in the borehole and plugging the system.

RISKS

During the course of this study, a register was created to capture risks and develop mitigating measures. A few of the most relevant ones will be discussed in this section such as the importance of a proper mix design, slicking of the borehole, and safety precautions at the toe of the borehole.

If a proper mix design is not formulated, one of the risks is segregation of material in the borehole. If this occurs the coarser material could accumulate, possibly causing borehole blockage, and/or variation in the strengths of the material once placed due to varying particle size. To mitigate this, QA/QC will be very important at the commencement of concrete/shotcrete delivery down the borehole to ensure that the proper slicking agent is used, and the proper admixtures are added to the mix design to prevent segregation. Continuous QA/QC will be required to ensure none of the parameters change over time.

Another risk is too great a velocity in the pipeline as the concrete/shotcrete plug exits the toe of the borehole. This may result in increased pressure, increasing the possibility of personnel injury, equipment

damage or creating a spill that could disrupt production. This again will need to be mitigated by QA/QC and proper mix design testing. Avoiding personnel injuries would include a detailed training program for all personnel associated with loading and transportation of material.

Wear on the borehole is also a risk for the future of the operation as the boreholes are required for life of mine paste backfill. If the borehole wear is extremely high, either new boreholes will need to be drilled, or casing of the existing boreholes would be required. Both conditions are costly and would likely cause delay in production if concrete/shotcrete and/or paste backfill could not be delivered underground as required. To mitigate this risk the borehole from surface will be twinned allowing a switchover to occur while the original borehole issues are addressed.

CONCLUSION

To this point, the conventional pipeline/borehole methods of delivering concrete and shotcrete in wet form have been through either vertical pipelines or boreholes. This study has provided empirical validation for the use of a dipped (sub-vertical) delivery system. As indicated, further mix designs and QA/QC procedures are still to be developed, however there do not appear to be insurmountable challenges with the approach presented in this paper.

An examination of Figure 1 shows that there is a significant area of the theoretical hydraulic grade line that is below the borehole profile even at a flow rate of 60 m³/hr and therefore an indication that even higher flow rates are possible.

Since the majority of the material will be delivered in batches, it will not be possible to operate the system under full flow conditions. Nonetheless, it should be possible to design a system that will minimize the increase in velocity and minimize wear in the borehole.

The risks that are associated with sending concrete/shotcrete through a dipped borehole can be mitigated by proper design of the mixes proper QA/QC, and training of personnel who will be in the vicinity of the operation. The development of the mix designs will include bench scale testing identifying the required admixtures to achieve the required strength and flowability without segregation. This would be followed, if deemed required, with some flow loop trials or by close monitoring of the initial pours for final adjustments.

Early installation of required life of mine infrastructure, in this case the paste backfill delivery system boreholes from surface, provides the opportunity for dual purpose use of such infrastructure. This facilitates a cost and time efficient approach to providing construction materials, such as concrete and shotcrete, required to move a deep mining project into the production phase.

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