Introduction

Cullinan Diamond Mine of De Beers is situated north-east of Pretoria in the Gauteng province of South Africa. The mine is a mechanized underground operation based beneath an open pit. The mining method is block cave mining in the existing block with an advanced undercut mining method for the new BB1 East Advanced Undercut Block. This mining method will serve as a testing ground of the future Centenary Cut Block from where diamonds will be mined at 1000 m below surface.

The mining haulages and undercut operations are supported by a combination of rock sealant, to prevent the ingress of water, followed by bolts and meshing or strapping, which is then covered in a layer of wet or dry shotcrete. The tunnel roadways are concreted with 45 MPa concrete; the ore passes as well as the drawpoints beneath the undercut level are concreted with 60 MPa concrete.

The current mining operation utilizes underground batching plants with the aggregates and cementitious binder being delivered through ore passes and pipeline, respectively, to the underground batching plants. The required concrete product is batched and transported to the utilization site in agicars.

With the advent of the BB1 East Advanced Undercut and the Centenary Cut the concrete and shotcrete demand is to increase significantly. It was decided to review a number of options for increasing concrete production.

The first option was to upgrade the underground operations and drill more ore passes for an additional batching plant.

Two more options were considered, both involving a surface batch plant and piping down either the available shaft structures or through a borehole.

The latter two options were discarded based on the risk of pipeline failure in the shafts and lack of experience with concrete transportation through pipelines.

Drilling began on the ore passes to the batch plants; however, owing to water ingress and the instability of the virgin rock, this route was abandoned and a borehole pipeline adopted.

The philosophy behind the borehole pipeline was to ensure that the pipeline was full to the collar with concrete. This is commonly referred to as a ‘full flow’ system in the backfilling industry. Simply put, a ‘full flow’ system requires that the frictional losses generated by the specific concrete product flowing through the pipeline be balanced against the available head, generated by gravity, and the concrete product density, owing to the depth to which the product is delivered underground.

The ramification of this pipeline requirement is that the batch plant output must match the output from the end of the pipeline into the underground storage system.

Design process

The design procedure followed to develop the Cullinan Diamond Mine concrete system is the same as that for the development of a typical backfilling system.

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† Cullinan Diamond Mine, De Beers.
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- Rock mechanic or engineering requirements for the shotcrete and concrete products, e.g. uniaxial compressive strength, shrinkage, wear rate, durability and energy absorption
- Environmental requirements of the product, i.e. water run-off and the associated chemical leaching
- Shotcrete and concrete mix designs, binder type, additives, aggregate type, transportable density
- Manufacturing plant design to produce the required shotcrete or concrete products
- Pipe loop tests on the proposed products to determine pipeline pressure gradients against flow rates
- Finalization of pipeline design based on frictional losses
- Risk assessments and audits
- Stress analysis of the pipeline and routing for structural purposes
- General arrangement diagrams and flow sheets for plant and distribution
- Presentation and finalization of the overall plant and distribution system
- Engineering drawings of the plant and distribution system
- Construction of the system
- Commissioning.

**Rock mechanic and engineering requirements**

The engineering requirements fell into two categories: one for concrete requirements and one for shotcrete requirements. The concrete requirements are based on uniaxial compressive strength (UCS) and slump. Three concrete strengths were required at a slump of 180 mm, 25, 45 and 60 MPa. The shotcrete requirements were more rigorous, including:

- A uniaxial cube compressive strength of not less than 45 MPa
- A uniaxial in situ core compressive strength of not less than 27 MPa
- An EFNARC energy absorption of not less than 700 joules
- A flow table of 650 to 700 mm

**Environmental requirements**

The underground environment on a kimberlite diamond mine is very susceptible to damage from water ingress, which results in the kimberlite degrading and losing all strength. It is therefore imperative that any products introduced into the mine do not suffer from excessive bleed water. This would pertain to the concrete products specifically where bleed water would run-off into the underground mine water. Shotcrete does not suffer from bleed water owing to the use of accelerator to rapidly set the sprayed product; however, the shotcrete must not increase the environmental dust or put hazardous materials into the atmosphere.

**‘Single aggregate’ mix design**

A crusher sand mix design was selected that met the 45 MPa UCS requirement. The basis for this selection was that it met the 45 MPa concrete requirement and that the removal of the superplasticizer and an incremental increase in the water content to meet the flow requirements would result in the 25 MPa product being achieved. Finally, the same mix design was used to achieve the 60 MPa requirement by increasing the superplasticizer content and reducing the water to achieve the required flow requirements.

**Manufacturing plant design**

There were three main design criteria:

- That the plant operation be as automated as possible
- That the system be capable of a minimum of 40 m$^3$/h output
- That redundancy was included throughout the system

**Pipe loop tests work and distribution system design**

The pipeline size was to be determined based on two issues:

- A flow rate of 40 m$^3$/h
- A full flow system.

In order to ensure that the pipe column remains full, it was necessary to carry out closed loop pipeline tests to determine the frictional losses associated with the proposed concrete product. This test work is carried out through a range of pipe sizes to determine the correct pipe size for the Cullinan Diamond Mine system. The pipe selection is to ensure that a flow rate of 40 m$^3$/h generates sufficient pressure loss throughout the pipeline to balance the available gravity head to meet the conditions for full flow. In order to carry out these tests, a closed loop pipeline through which the specific product is recirculated and the transport parameters are measured, was used.

**The closed loop pipeline**

**Description of the test facility**

Figure 1 is a simplified plan view of the facility that comprises the following main components:

- Progressive cavity pump: an Indura 120/1 Howden Progressive cavity pump with a flow output capacity of 110 m$^3$/h at a discharge pressure of 1500 kPa with a 75 kW variable frequency drive.
- The standard 80 and 150 mm nominal piping on the pump discharge was fitted with a pressure transmitter and thermocouple to record the pump output pressure and the temperature.
- 50 mm to 250 mm nominal bore test pipelines were provided as test sections in the standard 80 and 150 mm pipelines.
- Only the horizontal test pipeline of 9.144 m was instrumented with differential pressure transducers. The pressure tappings were spaced 6 m apart.
- Four types of magnetic flow meters are installed in the vertical section of the pipelines
- Nucleonic densimeters are installed in the vertical pipe ranges
- The test pipelines were connected to the loop manually using Trucking and Engineering couplings.
- A control cabin contained the variable frequency drives, instrument panels and operator facilities.

**Pipe loop details**

All the piping in the test loop is ASTM A106 grade B. The test diameter lengths and measured internal diameters are presented in Table I. Lengths were measured using a steel tape measure.

The pipe loop measures 35 170 mm in length of which 8 900 mm is the test pipe installation and 26 270 mm is 150 or 80 mm nominal bore schedule 40 ASTM A106 grade B pipe. The storage hopper has a volume of approximately 300 litres. The total volume of the system with a 150 mm test pipe is 1.122 cubic metres.
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Instrumentation calibration

The instruments were connected to an Endress & Hauser Memograph data logging system in the control cabin. The sensors monitored were:

➤ The flow rate through three Endress & Hauser magnetic flowmeters and one Krohne magnetic flow meter
➤ The differential pressure via the Endress and Hauser Deltabar S FMD 633 unit
➤ The absolute pressure at the pump output via the Endress & Hauser Cerebar M pressure gauge
➤ The relative density measured by a Process Automation nucleonic densitometer
➤ The power requirement of the pump measured in kW
➤ The pump rotation speed in RPM
➤ The concrete temperature through an Endress & Hauser thermocouple.

Instrumentation and data acquisition

The procedures used to calibrate the instruments are summarized in Table II.

Test facility operation

Raw materials preparation

All the concrete products were prepared manually by repacking the aggregates from the bulk bags into 25 kg bags. These bags together with the other raw materials were then blended in a RamboMix unit, comprising a 200 litre pan mixer and a positive displacement piston pump and pumped into the Howden Indura positive displacement pump, which then pumped the concrete product around the pipe loop. In all cases the product in the Rambo Mix was blended to a flow table of less than 700 mm.

Closed loop test sequence

The basic pipe loop test procedure is summarized as follows:

➤ The test section to be used was connected directly into the standard pipeline size using Trucking and Engineering couplings. In this case the standard pipeline used was the 150 mm ASTM A106 grade B pipe.

Table I

<table>
<thead>
<tr>
<th>Pipe loop parameter</th>
<th>Nominal diameter</th>
<th>Internal diameter</th>
<th>Test length</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 mm</td>
<td>77.9 mm</td>
<td>9.144 m</td>
<td>Differential pressure transducer</td>
<td></td>
</tr>
<tr>
<td>100 mm</td>
<td>102.3 mm</td>
<td>9.144 m</td>
<td>Differential pressure transducer</td>
<td></td>
</tr>
<tr>
<td>150 mm</td>
<td>154.1 mm</td>
<td>9.144 m</td>
<td>Differential pressure transducer</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1—The closed loop pipeline system

Figure 2—Clear water tests in the 80 mm pipeline
The differential pressure transducer was attached to the test pipeline and the pressure tappings flushed to ensure that no material impeded the transfer of pressure to the pressure diaphragms. The concrete product was mixed in the RamboMix to the correct flow table measurement. The progressive cavity pump recirculated water through the pipeline at a constant velocity to slick the pipeline. The water was drained from the pipeline. The concrete product was transferred from the RamboMix to the progressive cavity pump hopper and slowly recirculated through the pipeline. The instrument signals were monitored. The concrete relative density was measured manually as well as through the nucleonic densitometer. If the relative density was acceptable, the data was recorded over a range of pump speeds. Data collection was controlled from the control cabin. The system was flushed at the end of a complete test. Flushing involved pumping the concrete into a hopper and then clearing the system with water and compressed air.

Data recording
Data points were collected continuously throughout the residence time of the test product within the closed loop pipeline. The specific test parameters were taken from this body of time-based data and plotted against each other to obtain the necessary relationships, specifically the frictional losses against the test product velocity for the specific relative density and pipeline inside diameter.

Test schedule
The summarized test schedule is given in Table III.

Commissioning tests
Clear water pipeline tests
It is standard practice to obtain clear water pipeline curves to ensure that the instrumentation on the pipeline is working correctly. Clear water tests were carried out to confirm the operation of the flow meters and pressure transmitters. These tests were carried out on the 80 and 100 mm pipelines as the accuracy of the differential pressure transducer did not allow for readings in the 150 mm pipeline. Figures 2 and 3 are the clear water tests for the 80 and 100 mm pipelines. The flow meter and the differential pressure transducers performance confirms that the equipment is operating correctly.

These test results are given using the Endress & Hauser Promag S with hard alloy electrodes. The Endress & Hauser Promag S with brush electrodes suffers from too much background noise and the Krohne Magnetic flow meter does not appear to work at these high relative densities at all.

Test results
Progressive cavity pump single aggregate results
Figures 4 and 5 are the results achieved for the single aggregate concrete. Figure 4 is a graph of the pipeline pressure gradient against flow rate for the different pipe sizes tested. Figure 5 is a graph of the pipe inside diameter against the pipeline pressure gradient.

Progressive cavity pump current shotcrete mix design results
Figures 6 and 7 are the same as for the single aggregate test results.

Discussion
In order to develop a full flow pipeline distribution system, it is necessary to have the pipeline frictional losses for the product to be transported so that the system operates at a velocity at which the system pressure losses, due to pipe friction, bends, entry and exit orifices, are just balanced by the gravity head due to the difference in elevation between the discharge point and the free surface of the product in the surface storage facility. In developing the flow rate frictional loss relationships, cognizance must be taken of the flow characteristics of the material to ensure that the correct relationships to fit the data are sought.

Table II
Instrument calibration description calibration method

<table>
<thead>
<tr>
<th>Description</th>
<th>Calibration method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endress &amp; Hauser magnetic flow metres 80 and 150 mm Sensor—Promag S</td>
<td>• The instrument span was set from 0 to 250 m³/h for the 150 mm flow metres</td>
</tr>
<tr>
<td>Transmitter Promag 35</td>
<td>• The output was checked against the mass of water diverted to a 220 t barrel</td>
</tr>
<tr>
<td>Krohne magnetic flow metres 80 80 and 150 mm</td>
<td>• The data was captured manually</td>
</tr>
<tr>
<td>Sensor—Altoflux IFS 4005</td>
<td>• The flow metres were compared to each other</td>
</tr>
<tr>
<td>Transmitter—Altoflux SC 150</td>
<td>• The magnetic flow metre readings were graphically compared to the pressure losses for water</td>
</tr>
<tr>
<td>Process automation nucleonic density metre</td>
<td>• The instrument span was set from 1 to 2.5 t/m³</td>
</tr>
<tr>
<td>Endress &amp; Hauser temperature probe</td>
<td>• The calibration constant and coefficient was determined for the set span</td>
</tr>
</tbody>
</table>

Table III
Test schedule pipeline test

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm</td>
<td>Set-up test loop and instrumentation</td>
</tr>
<tr>
<td>80 mm</td>
<td>Flow metre calibration using Hazen Williams formula and pipe loop pressure testing and instrumentation calibration</td>
</tr>
<tr>
<td>150 mm</td>
<td>Clear water tests and tests of the specific concrete products</td>
</tr>
<tr>
<td>100 m</td>
<td></td>
</tr>
<tr>
<td>80 mm</td>
<td></td>
</tr>
</tbody>
</table>
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Figure 3—Clear water tests in the 100 mm pipeline

Figure 4—Graph of pressure gradient against flow rate for the single aggregate concrete

Figure 5—Graph of pressure gradient against pipe inside diameter for the single aggregate concrete
In general terms, solids liquid mixtures can be divided into three categories:

➤ Where the liquid, generally water, retains its own properties and carries within it solid particles that are not suspended but saltate along the pipe bottom
➤ Where the liquid, generally water, typically approximates its own properties and carries within it very fine solids particles that are suspended within the fluid
➤ Where the liquid, generally water, carries within it solids particles in such a high concentration as to markedly change the properties of the carrier fluid.

It is under this last category that concrete falls. Figure 8 is a graphic representation of the various shear rates versus wall shear stress relationships for different materials.

To calculate the shear rate and wall shear stress, the equations below are used:

Shear rate \[ \dot{\gamma} = \frac{8V}{D} \]

where \( V \) is the velocity of the transported product

Wall shear stress \[ \tau_w = \frac{\Delta P D}{4L} \]

where \( \Delta P \) is the pressure gradient

\( D \) is the pipe inside diameter

\( L \) is the length over which the pressure gradient was measured.

Figures 9 and 10 are the graphs of shear rate against wall shear stress for the single aggregate and current shotcrete mix designs. It will be noted that the relationships are not Bingham plastic but more Pseudo Plastic in nature. A further difference that makes the relationships not true Pseudo...
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Plastic is that there appears to be a yield stress. What this means is that the relationship does not go through zero but that a certain amount of force needs to be applied to the product before the material moves, resulting in a displacement up the Y-axis of the Pseudo Plastic relationship. This displacement results in a Yield Pseudo Plastic relationship being applied. The equation is not given here for calculating the wall shear stress but the calculated relationship is given as the solids lines in Figures 9 and 10.

The Yield Pseudo Plastic relationship gives up three indices, the yield stress \( (\tau_0) \) the fluid consistency index \( (K) \) and the Flow behaviour index \( (n) \).

It can be seen that this relationship fits the data well and will allow for predictive analysis of other pipe sizes.

In determining a pipe size for the Cullinan Diamond Mine for the single aggregate concrete, Figures 5 and 9 should be inspected.

There are 8 main points to consider when designing a full flow system.

➤ Typically in slurry systems, the transport velocity \( (V) \) of the slurry must be significantly higher than the deposition velocity \( (V_d) \) to prevent the slurry from settling out. This characteristic does not occur in the concrete system as the product does not settle.

➤ The transport velocity \( (V) \) must be kept as low as possible to minimize friction losses and pipe wear. Pipe wear is proportional to product velocity, \( W \propto V^k \), where \( k \) is an exponent between 1 and 4.

➤ Standard pipe sizes are preferred to minimize the cost in stock and fittings.

➤ In vertical columns, the maximum flow rate is at the point where the frictional losses exactly equal the available static head.

➤ The maximum working pressure in the system is generally found at the bottom of vertical columns, being determined by the frictional losses in the horizontal pipelines to reach the discharge.

➤ Usually pipe columns have to be installed in shafts that are already equipped. This system, however, is going to utilize a borehole.

➤ Rupture discs should be provided at the points of maximum pressure in case of blockage in the pipe.

➤ Provision must be made for the flushing of lines before and after transport.

A step-by-step procedure for the system design is given here to ensure that data from each step is available for the subsequent step.

➤ **Step 1: Concrete requirement**—this has been predetermined as approximately 2 500 m\(^3\)/month.

➤ **Step 2: Determine the total pipeline length**—the static or pressure head is calculated by taking the change in elevation of the pipe column between the shaft collar and the level that the column feeds to. This distance, in metres, is multiplied by the gravitational constant and the slurry relative density to calculate the static head in kPa.
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\[ \text{Static head} = \Delta H \times g \times SG \Delta. \]

where
\( \Delta H \) is the change in elevation of the total vertical distance of the pipe column (m)
\( g \) is the gravitational constant, 9.81 m/s²
\( SG \) is the specific gravity of the concrete

➤ **Step 3: Determine the total pipeline length**—this is simply the total length of the pipeline from the shaft collar to the underground plant.

➤ **Step 4: Piping selection**—is based on the pressure rating of available piping and on the velocity through the pipeline to achieve the required flow rate of 40 m³/h. The concrete transport velocity is calculated by dividing the required flow rate (m³/s) by the internal cross-sectional area of the pipe (m²). Ideally the concrete velocity should be in the order of 1 m/s or less.

➤ **Step 5: Determination of frictional losses**—once the initial pipe size(s) have been chosen, the frictional losses for a range of velocities, at the required concrete relative density, need to be determined in order to balance the system. The pipe pressure gradient (kPa/m), for a specific concrete relative density and velocity, when multiplied by the total pipeline distance, returns the total pipeline frictional losses. The total pipeline frictional losses must equal the static head for the system to be balanced.

➤ **Step 6: Balancing the full flow system**—should the total frictional losses not equal the available pressure head, a number of options are available:
- Decrease the pipe diameter. This will increase the frictional losses but will also increase the concrete velocity and subsequently the pipe wear rate
- Increase the concrete relative density. This will increase the frictional losses; however, this also increases the available pressure head requiring increased pipe pressure ratings
- Utilize some form of energy dissipation.

Option three is usually the easiest and most cost-effective solution. It is not the preferred option in this case owing to the physical characteristics of the concrete and the difficulty of cleaning the system. The difference between the pressure head and the total frictional losses is the amount of energy that needs to be dissipated.

In the case of Cullinan Diamond Mine, the concrete distribution system design is for a maximum of flow rate of 40 m³/h.

Ideally this is to be carried out at a pipeline velocity in the order of 1 m/s.

The approximate height from surface underground is 714 m with a further 230 m to the underground storage facility.

This results in a static head or driving force of approximately 15.40 MPa (714 x 9.81 x 2.2).

The total pipeline length is approximately 962 m, excluding the surface 30 m feeding the borehole, which is fed by a piston pump. Therefore, in order to achieve a full flow condition in the pipeline, a frictional loss per metre of pipe of approximately 16 kPa/m must be achieved.

From Figures 5 and 7 for frictional losses versus pipe inside diameter it can be seen by looking at the 16 kPa/m loss that the pipe inner diameter requirement at a flow rate of 40 m³/h is approximately 124 mm.

If we now carry out the same procedure with Figures 9 and 10 for the Yield Pseudo Plastic relationship, we get a required wall shear stress for the single aggregate of:

\[
\frac{\Delta PD}{4L} = K \left( \frac{8V}{D} \right)^n
\]

16000 x 0.124
\[
\frac{4}{0.124} = 496 \text{ Pa}
\]

and a shear rate of:

\[
8 \times 0.92 = 9.3 \text{s}^{-1}
\]

The actual result from Figure 9 for a loss of 16 kPa/m is a shear rate of 57 s⁻¹ or a concrete velocity of 0.93 m/s, i.e. a flow rate of 38 m³/h in a 124 mm ID pipe as opposed to 40 m³/h.

Similarly for the current mix design, the calculated wall shear stress and shear rate are the same as for the single aggregate but the actual result from Figure 10 results in a flow rate of 29 m³/h

**Conclusions**

Blockages must be avoided and designed out of the system through correct flushing procedures and monitoring of pumping pressures and frictional losses.

The single aggregate mix designs can be transported by pipeline with little concern for changes in pipeline diameter even from 150 mm to 80 mm.

The 60 MPa current concrete mix design is not capable of being pumped by the progressive cavity pump and therefore these results were generated by comparison with a positive displacement piston pump. This product can be pumped by a piston pump and can be transported by pipeline. It is necessary, however, to ensure that the pipeline is free of discontinuities.

In all cases for the current and proposed products a ‘full flow’ system can be achieved based on the available gravity head and total pipeline frictional losses. There will, however, be differences in flow rates for the different products.

The results presented, including the relationships generated based on a Yield Pseudo Plastic model, in this report are sufficient to design any concrete transport system on Cullinan Diamond Mine for the tested single aggregate and concrete and shotcrete products.

The results on pipe sizing proposed in this report for the cullinan Diamond Mine are by no means the definitive design for the proposed system and need to be comprehensively analysed when the exact pipeline routing is finalized.

**Acknowledgement**

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