ABSTRACT

Cleveland Potash Limited produces two waste products: a salt centrifuge cake and clay filter cake. Currently the waste is re-pulped with sea water and discharged into the North Sea. Due to trace quantities of mercury and cadmium in the clay, the permitted amount of waste that the company can discharge into the sea will be reduced over the next few years.

Cleveland Potash proposes to place the filter cake waste as backfill in worked out areas to reduce the mine’s environmental impact and allow the mine to operate at maximum tonnage.

This paper describes the test rig built at the mine and test work conducted to obtain backfill slurry flow data for the design of a system to deliver backfill to old underground workings.

1 INTRODUCTION

Cleveland Potash Limited produces approximately 55% of the United Kingdom’s potash (potassium chloride) supply, along with halite (rock salt) as a co-product. The facility is located in the North York Moors National Park and comprises a deep underground mine and surface process plant. Shaft sinking operations commenced in 1969, with the first shipment of potash product taking place in 1973.

The Cleveland Potash process plant produces two waste products: a centrifuge cake consisting of coarse salt produced at a rate of around 190 t/h; and a filter cake composed of salt, calcium sulphate and insoluble montmorillonite clays produced at 30 t/h. Currently all process waste is re-pulped with sea water and discharged into the North Sea. Due to trace quantities of heavy metals (mercury and cadmium) in the insoluble clays, the permitted amount of insoluble waste the mine can discharge will be reduced substantially over the next few years.
The mine initiated a research project, funded in part by the EU LIFE Environment Programme, to demonstrate the viability of disposing of the clay waste underground in mined out areas as a high density backfill. The gravity head available is to be used to feed the backfill via a piping system to the old underground workings. This will reduce Cleveland Potash’s environmental impact, while allowing the mine to operate at its maximum tonnage, and even increase the tonnage milled, in line with strategic operational planning.

This paper describes the on-site test work performed by Paterson and Cooke Consulting Engineers (Pty) Ltd on behalf of Cleveland Potash to provide data for the design of the backfill piping system and to demonstrate the viability of the concept.

2 INVESTIGATION OBJECTIVES

Specific objectives of the test programme were to:

- demonstrate the feasibility of a gravity-fed backfill distribution system,
- identify the most suitable composition and optimum density of the backfill by analysis of the flow behaviour of the range of slurries considered by Cleveland Potash Limited,
- obtain sufficient backfill flow data to characterise the slurry for the purpose of designing the underground backfill distribution system, and
- investigate whether flushing of the system was required following system shutdown.

Initially it had been thought that the salt waste should be mixed with the clay filter cake to increase the density that could be placed underground as addition of the salt waste reduced the viscosity of the backfill. Tests on various salt and clay mixes were conducted and the data analysis showed that although higher densities could be achieved, the effective clay tonnage placed per unit volume underground decreased. Further investigation of mixing the salt waste and filter cake was discontinued.

3 ON-SITE PIPE LOOP TESTS

3.1 Pipe Loop Test Facility

It was decided to conduct the pipe loop tests on site for the following reasons:

(i) logistically it would have been difficult to transport the required quantities of material to a commercial test facility,
(ii) preliminary work had shown that the filter cake and salt properties changed with time and so it would be preferable to conduct the pipe loop tests with fresh material, and
(iii) the test loop would demonstrate the viability of a gravity flow distribution system to mine personnel.

A test facility was designed and constructed at the mine plant to meet the investigation objectives. The test facility, shown schematically in Figure 1, comprised of the following main components:

- A conveyor feeder system to feed the filter cake into the backfill mixing tank.
• A backfill mixing tank with mechanical mixer, to re-pulp the sea water and filter cake into a slurry.
• A pump to deliver the backfill to a constant head tank.
• A constant head tank to maintain a constant head feed to the two test pipe loops.
• Two test pipe loops (100 mm and 150 mm) fed by the constant head tank run vertically to the ground floor level and then in a horizontal loop to discharge back into the backfill mixing tank.
• Butterfly valves near the discharge end of each of the two test pipe loops to control the backfill flow rate during a test.
• The two test pipe loops were instrumented to measure backfill density, flow rate and pressure at a point just upstream of the butterfly valves.
• A heat exchanger was incorporated to limit heat build up in the re-circulating backfill.
• An overflow line back to the mixing tank.

![Figure 1: Schematic of test rig](image)

Backfill was pumped up to the constant head tank. An overflow from the constant head tank was maintained at all times. This was done by ensuring that the flow rate in the feed to the constant head tank was always greater than the flow rate in the test pipe loop.
The backfill flow through the test pipelines was gravity driven. The ratio of vertical to horizontal piping in the test rig was chosen to be similar to the ratio of shaft depth to the anticipated underground distribution network length. This ensured that it was possible to test over the expected range of backfill mixture densities. Figure 2 shows a view of the mixing tank and feed pump.

![Test rig mixing tank and feed pump](image)

Figure 2: Test rig mixing tank and feed pump

The instrument outputs were logged using a multi-channel data acquisition unit linked to a computer. Purpose written software allowed for real-time plotting of each data point immediately onto a system curve plot (friction pressure loss versus flow rate) as it was recorded. This allowed the test personnel to check that there were no significant problems with the data measurement.

3.2 Test Procedure

A range of backfill densities was tested in the 100 mm and 150 mm pipe loops. The maximum density tested was that at which the static head available was insufficient to cause any significant flow.

The backfill was prepared by adding filter cake to sea water in the mixing tank while circulating through the constant head tank and one of the test pipelines to achieve the desired density. A nucleonic density meter was used to record the backfill density and confirmed with manual samples taken at the start and end of each test by sampling from a tapping point after the pump discharge.

During a pipe loop test, data points were recorded for a range of backfill flow rates. Each data point comprised a reading of backfill flow rate in the test pipe loop, pressure at the pressure transmitter, backfill density and backfill temperature. The backfill flow rate was adjusted by means of the butterfly valve. Typically a test was started by taking a reading at the maximum flow rate. The flow rate was reduced for subsequent readings. A number of readings were
repeated at higher flow rates at the end of the test to check for any change in backfill flow behaviour over the test period.

3.3 Determination of the pipe friction losses

Figure 3 shows a definition sketch of the measurements for the pipe loop tests. Point 1 is at fluid surface level in the constant head tank. Point 2 is at the pressure transmitter just before the butterfly valve.

Figure 3: Definition sketch for calculation of pressure losses

The pressure loss between Points 1 and 2 can be calculated by applying Bernoulli’s equation and noting that $P_1$ and $V_1$ (the pressure and velocity at fluid surface of constant head tank) are zero:

$$
\Delta P_{\text{loss}} = \rho_m g \Delta h - \frac{\rho_m V_2^2}{2} - P_2,
$$

where $\Delta P_{\text{loss}}$ = pressure losses between Point 1 and Point 2 (Pa), $\rho_m$ = backfill density (kg/m³), $G$ = gravitational constant (m/s²), $\Delta h$ = static height or $z_1 - z_2$ (m), $V_2$ = velocity at Point 2 (m/s), $P_2$ = pressure at Point 2 (Pa).

A typical measured data set plotted in the form of a system curve graph is shown in Figure 4.
In order to rheologically characterise the backfill, it is necessary to extract the pipeline friction pressure gradient from the measured system pressure loss, which comprises both pipe and fitting losses. The pipe wall friction can be determined from:

$$\Delta P_{\text{friction}} = \Delta P_{\text{losses}} - \Delta P_{\text{fittings}}.$$  \hfill (2)

This approach to establishing the friction pressure gradient was adopted in favour of the more conventional laboratory method of measuring a differential pressure between a pair of tappings in a straight pipe for a number of reasons. The primary factor in this decision was the desire to simplify the test operation as far as possible. Past experience with differential pressure measurements has shown that great care needs to be taken in preparing the static pressure tapping holes in the pipe wall and in keeping these and the capillary tubes to the differential pressure transducer clear. The constant head plus single pressure measurement point approach proved to be very successful for the on-site tests.

The fittings between the constant head tank outlet and the test pipe loop discharge were documented and the total pressure loss due to fittings in the system calculated using published head loss coefficients (1).

$$\Delta P_{\text{fittings}} = \sum \rho_m \frac{k_i V_i^2}{2},$$  \hfill (3)

where $\Delta P_{\text{fittings}} =$ total pressure losses of system fittings (Pa), $k_i =$ head loss coefficient for fitting i, $V_i =$ velocity in fitting i (m/s).
For the head loss coefficient values, \( k_i \), the coefficients used are those established for turbulent flow of Newtonian fluids. In turbulent flow the loss coefficient is a constant and is similar for both Newtonian and Non-Newtonian fluids (2). For laminar flow these fitting losses do increase significantly as the flow rate decreases (2, 3). The information available on the fitting loss coefficients is limited and so it was decided to use the coefficients for turbulent flow. This approach meant that although the fitting losses were under-predicted, the friction losses calculated were over-predicted for laminar flow. It should also be noted that the pressure loss due to the fittings was not a significant percentage of the total pressure loss in the system.

3.4 Rheological Characterisation

A further complication was that each test pipeline included sections of both steel and polyethylene piping of slightly different inner diameters. The pipeline friction pressure loss can be expressed as:

\[
\Delta P_{\text{friction}} = \Delta P_{\text{steel}} + \Delta P_{\text{polyethylene}}
\]

\[
= \frac{4\tau_{0,\text{steel}}L_{\text{steel}}}{D_{\text{steel}}} + \frac{4\tau_{0,\text{polyethylene}}L_{\text{polyethylene}}}{D_{\text{polyethylene}}},
\]

where \( \tau_0 = \) wall shear stress (Pa)
\( L = \) pipe length (m)
\( D = \) diameter (m).

The filter cake slurry is a homogeneous, non-Newtonian mixture and was characterised as a Bingham Plastic fluid. As such, the shear stress at the pipe wall can be expressed by:

\[
\tau_0 = \frac{8V}{D}\mu_{BP} \left[ 1 - \frac{4}{3}\left( \frac{\tau_{y,BP}}{\tau_0} \right) + \frac{1}{3}\left( \frac{\tau_{y,BP}}{\tau_0} \right)^4 \right],
\]

where \( V = \) fluid velocity (m/s)
\( \mu_{BP} = \) plastic viscosity (Pa.s)
\( \tau_{y,BP} = \) Bingham yield stress (Pa).

Using Equation 4 and 5, the rheological parameters \( \tau_{y,BP} \) and \( \mu_{BP} \) are evaluated for each of the data sets using an iterative routine to minimise the error between the measured and calculated pressure loss for the laminar flow data. The rheological parameters are shown as a function of backfill density in Figure 5 and Figure 6, together with correlations established to allow evaluation of the rheological parameters at any intermediate backfill concentration.
Figure 5: Filter cake backfill plastic viscosity, $\mu_{BP}$ as a function of backfill density

\[ \mu_{BP} = \mu_0 \left(1 - \frac{C_v}{0.36}\right)^{-0.9} \]

Figure 6: Filter cake backfill Bingham yield stress, $\tau_{y,BP}$ as a function of backfill density

\[ \tau_{y,BP} = 50 - \frac{C_v^{1.8}}{0.47 - C_v} \]
In Figure 5 and Figure 6 there are two outlying data points from tests conducted on a day when the filter cake was coarser than normal. The yield stress measured for these tests was notably lower than for other tests and the plastic viscosity considerably higher.

Using these correlations for determining $\mu_{BP}$ and $\tau_{y,BP}$, it is possible to compare the predicted system curves with the test data. Figure 7 shows the comparison of measured and calculated pressure losses for the 100 mm pipe loop for three of the tests. The calculated pressure loss curves showed reasonable agreement with the measured data for both the pipe sizes and over the full range of densities. The turbulent pressure gradients are determined using the pseudo fluid model.

![Figure 7: Measured and calculated system pressure losses in 100 mm pipe loop](image)

3.5 Pipeline Shutdown and Re-start

The possibility of re-starting slurry flow after a shut-down without flushing the piping system was investigated. The test pipelines were left to stand overnight full of slurry from the last test of each day with the control valve fully shut. Flow was initiated the following morning by first circulating slurry from the mixing tank through the constant head tank. The pipeline flow control valve was then opened. Flow was initiated immediately under the gravity head available. This indicates that there was no significant segregation of the slurry or tendency for it to plug the line after a shut-down of 12 hours. This was corroborated by further tests done at a later stage which indicated that system could be left for longer than 12 hours without re-start problems.
4 ACHIEVEMENT OF OBJECTIVES

The test programme successfully achieved the objectives:

- The use of the constant head tank to provide a gravity head for the test pipe loops successfully demonstrated the proposed gravity pressure driven backfill system to the mine.
- The filter cake material is the material that needs to be placed underground and it was shown that it was unnecessary to mix salt waste with the filter cake to achieve the required placement densities. More effective use of the limited underground placement volume would be achieved by placing filter cake on its own.
- The backfill slurry was rheologically characterised with sufficient accuracy to enable the hydraulic design of the underground distribution system and the preliminary engineering design of the surface plant to proceed with confidence.
- The test rig was successfully restarted after a shutdown period of more than 12 hours. It is not necessary to flush on start-up or shutdown and the system can be shutdown with backfill in the piping for limited periods without risk of blockage or settling.

5 CONCLUDING REMARKS

Although the test rig designed, constructed and used in these backfill characterisation tests, will not be able to predict flow behaviour of backfill as accurately as is possible with a laboratory pipe loop, the results obtained were sufficient for the required purposes.

In addition valuable experience was gained of the material handling and mixing characteristics of the filter cake. This was particularly useful during the design of the surface plant.

The difficulties encountered during the test programme were successfully overcome and valuable lessons were learnt for future on-site test work.
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