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Feasibility study of a 180 km nickel ore pipeline—rheological factors influencing slurry pipeline design

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Gladstone Pacific Nickel Limited (GPNL) is proposing to develop the Marlborough nickel deposit in central Queensland and the Yarwun Refinery in Gladstone, Australia. The project proposes to connect the two sites with a DN 500, single pump station slurry pipeline, transporting up to 4 Mtpa of nickel laterite ore as slurry 180 km from Marlborough to Gladstone. Slurry viscosity is a key parameter influencing pipeline design. Not only is the slurry viscosity relatively high, requiring pumping at low concentrations, around 30% by weight, but the viscosity (yield stress and plastic viscosity) increases with shearing or agitation. It is argued that the viscosity changes can be analysed in terms of total energy input, including energy input during grinding. The slurry viscosity is therefore expected to increase along the pipeline and the pumping concentration must be low enough such that the increase in yield stress does not cause transition to laminar flow towards the end of the pipeline.

The base viscosity of two ore types is determined using a rotational viscometer for minus 212 micron slurries. Viscosity variations with ore particle sizes of d_{99} 212, 425 and 600 microns are investigated. For each of these particle sizes the expected increase in viscosity during pipeline transport is simulated on a laboratory scale by agitation with a turbine mixer in a baffled container to give the same equivalent unit energy input as will occur in the pipeline. Tests were also conducted on the d_{99} 425 micron slurry in a 2.7 metre diameter DN 200
Wheelstand, rotated for the 23 hour transit time and at a similar relative velocity as in the pipeline. Based on the Wheelstand test results the yield stress is expected to increase by a factor of 3.1 during pipeline transit. The preliminary design allows for a reduced pumping concentration to accommodate this increase in yield stress towards the end of the pipeline.

Introduction

The Gladstone Nickel Project (GNP) comprises the Marlborough mine and Coorumburra ore preparation plant to be located 30 km to the south of Marlborough and the Yarwun Refinery, to be located in the Gladstone State Development Area (GSDA), Queensland. The Coorumburra ore preparation plant will be connected to the Yarwun Refinery by a 180 km pipeline, pumping nickel laterite ore as slurry from Marlborough to Gladstone.

Geology and metallurgy

Geology

The Marlborough nickel deposit is contained within a laterite that overlies the Princhester Serpentinite. The Princhester Serpentinite lies in the northern part of the New England Orogen and has been described as the largest ultramafic mass in Eastern Australia (Murray, in prep 2006).

The Marlborough nickel laterites exhibit little evidence of the original lithologies, with serpentinite, often veined with magnesite, outcropping in stream beds and low lying areas. Chromitite pods and lenses occur sporadically in the area. Mafic dykes intrude the serpentine, and recent mapping has shown these to trend mainly NNE and NW (Humphries, 2006).

Metallurgy

During 1998 and 1999, Preston Resources undertook an extensive beneficiation testwork programme at the Ammtec facilities in Perth, Western Australia, investigating a flowsheet, which required material for the HPAL (high pressure acid leach) autoclaves only (Ammtec, 1999). It was recognized early that there was potential for screening, scrubbing, attritioning and other size separation techniques to deliver significant benefits to the project economics. In 2005, GPNL undertook further testwork at the Oretest facilities in Perth, Western Australia, with a view to supplying beneficiated material to the Yarwun Refinery (SGS Lakefield Oretest, 2006).

The testwork conducted with the Marlborough nickel laterites at Oretest has demonstrated the amenability of the low magnesium saprolite (LMS) to beneficiation. Based on batch and pilot plant testwork the LMS ore preparation plant will consist of scrubbing, screening, attritioning and grinding.

The testwork at Oretest also demonstrated that the high magnesium saprolite (HMS) component of the deposit is not as amenable to beneficiation and it is proposed that this ore type be ground to the particle size required for slurry pumping. The two ore slurries will be pumped alternately 180 km through a slurry pipeline from Marlborough to the proposed Yarwun Refinery, near Gladstone. The slurry pipeline will consist of a DN 500, HDPE lined steel buried pipeline with a single pump station at Marlborough. The pipeline will transport up to 4 Mtpa of beneficiated nickel laterite ore as slurry at 29% to 33% solids concentration by weight.

The Marlborough nickel laterite ore slurries exhibit relatively high viscosity and the viscosity increases with shearing or agitation. The viscosity is therefore expected to

increase along the pipeline and the pumping concentration must be low enough such that the increase in yield stress does not cause transition to laminar flow towards the end of the pipeline.

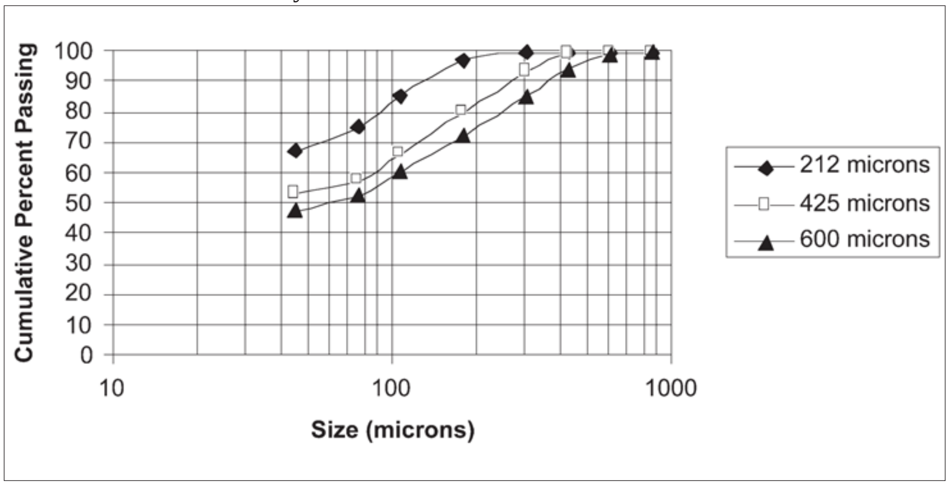
Comparative rheological testwork was conducted at Oretest to confirm the impact on ore slurry viscosity with saline water and fresh water. Overall, the slurries prepared in saline water exhibited improved viscosity in comparison to the slurries prepared in fresh water. The saline water was ultimately selected on the basis of downstream processing benefits.

Beneficiated LMS ores ground to d_{99} 212, 425 and 600 microns were investigated. Figure 1 shows particle sizings.

The solids specific gravity (SG) of the LMS ore is 2.85 and the HMS ore 2.83. The nickel ore slurries settle extremely slowly. For example, settling tests on a 24% concentration d_{99} 212 micron LMS slurry resulted in the interface level between slurry and clear water falling only to 91% of the original height after 71 hours' settling. Over the same period a 34% concentration d_{99} 212 micron HMS slurry settled to 84% of the original height.

Rheologocal investigations

Viscometer and data analysis



Rheological investigations were conducted using a Contraves RM115 rotational viscometer using a bob and cup radius ratio of 0.947 and a gap of 1.30 mm over a 15 speed range representing shear rates from 8.9 s^{-1} to 661 s^{-1}. Data was analysed in terms of the Bingham Plastic model, which is typical for laterite slurries.

Figure 1. Particle sizings

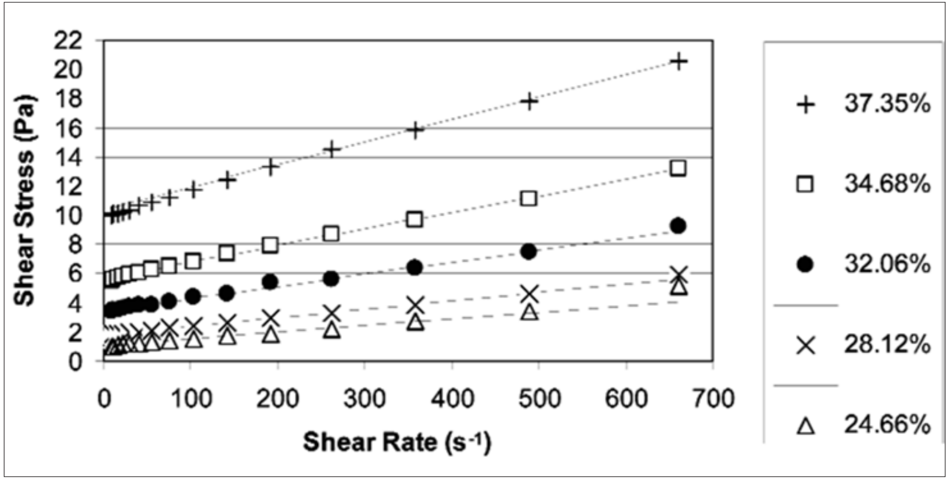
Figure 2 shows typical shear stress versus shear rate data, with straight lines fitted to the high shear rate data. The Bingham plastic model is seen to describe the data well.

Concentrations were determined by oven drying. The dry mass was measured immediately after removal from the oven to avoid erroneous readings due to water absorption from the atmosphere. The true solids' concentration was obtained from the measured concentration after compensating for the mass of dry salt from the evaporated saline water.

Basic rheological properties of ore slurries

The LMS ore represents approximately 75% of the total ore resource and also exhibits the highest viscosity. For these reasons the bulk of the testwork was conducted on LMS ore slurries. The HMS slurries exhibit similar trends to the LMS slurries, but the lower viscosity allows pumping at four per cent higher concentration.

The yield stress results for the d_{99} 600, 425 and 212 micron LMS samples are compared in Figure 3. Also shown in Figure 3 as a dashed curve are the results for the first LMS sample received. The first d_{99} 212 micron LMS sample exhibits a much higher yield stress equivalent to about a six percentage point concentration shift. Investigations into the reasons for this revealed that after being produced, the first sample was stored in an agitated tank with additional pump recirculation for a total of 70 hours. This shearing and agitation had increased the viscosity. This is discussed in further detail below.



As would be expected, for any particular concentration, the yield stress increases as the particle size decreases. Apart from the effect of particle size, the increased yield stress may also be a function of the increased energy input during grinding. This is also discussed in below. Figure 4 shows the plastic viscosity comparisons for the same slurries. Similar trends are evident although the shift in concentration is less.

Figure 2. Typical flow curves minus 425 micron slurry

Effect of agitation

Calculations indicate that energy input per unit volume during pipeline transit will be approximately 4.3 kWh/m^3. The effect of agitation on slurry rheology was investigated using a laboratory-scale agitator. An equivalent 4.3 kWh/m^3 energy per unit volume input was achieved by agitating at 1 600 rpm using a four-blade turbine impeller of diameter 25 mm with blades 8 mm deep X 1 mm thick. The clear acrylic container was of diameter 70 mm and height 100 mm and included four vertical baffles spaced at 90°,

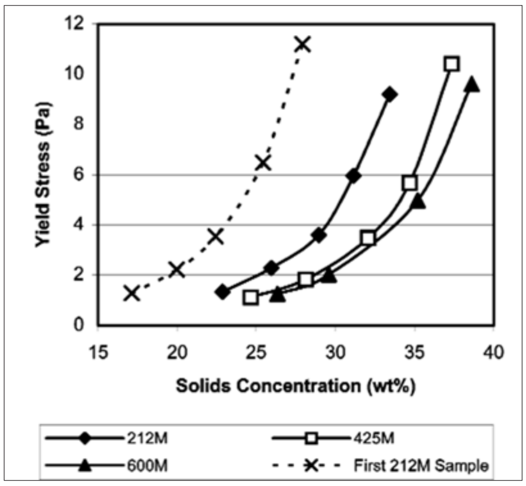


Figure 3. Yield stress comparisons

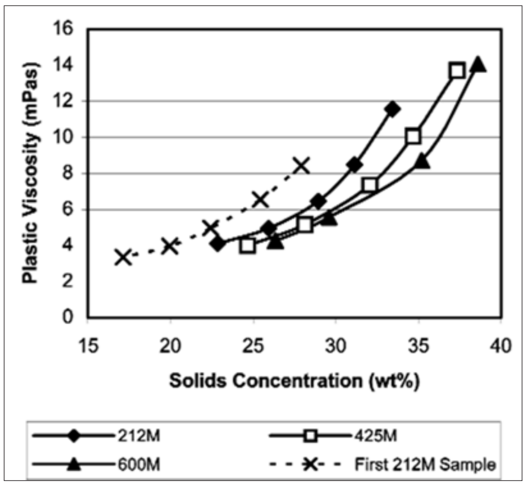


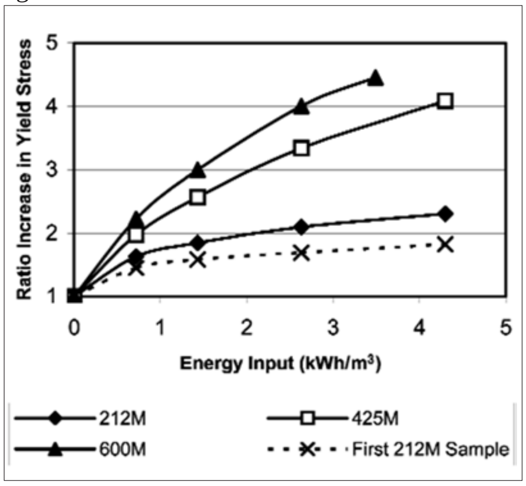
Figure 4. Plastic viscosity comparisons

of height 100 mm and width 8 mm and thickness 2 mm. During the test the container was filled to height 70 mm with slurry. The turbine was positioned 25 mm from the bottom of the container.

The turbine mixer had previously been calibrated using various Newtonian fluids over a range of speeds using the viscometer to measure the torque. For Reynolds numbers above 100, which almost certainly applies in the current tests at 1 600 rpm, a constant Power Number (N_p) of 5 applies and power inputs were calculated assuming $N_p = 5$.

For a slurry at 25% concentration the slurry density is 1 200 kg/m^3 and the calculated agitator power is 1.11 W. The volume of the container is 3.85×10^{-4} m^3. Ninety minutes agitation therefore equates to the calculated 4.3 kWh/m^3 energy input during transit through the pipeline. The agitator speed of 1 600 rpm also equates to an agitator tip speed of 2.09 m/s, which is similar to the expected pipeline velocity.

The agitation tests were conducted on d_{99} 212, 425 and 600 micron slurries with initial yield stress values around 4.5 Pa, which was expected to be the likely yield stress at the start of the pipeline. The actual solids concentrations were: d_{99} 212 micron 30.35%, d_{99} 425 micron 34.27%, d_{99} 600 micron 36.35% and first d_{99} 212 micron sample 23.3%. Rheological measurements were conducted at regular intervals during agitation.



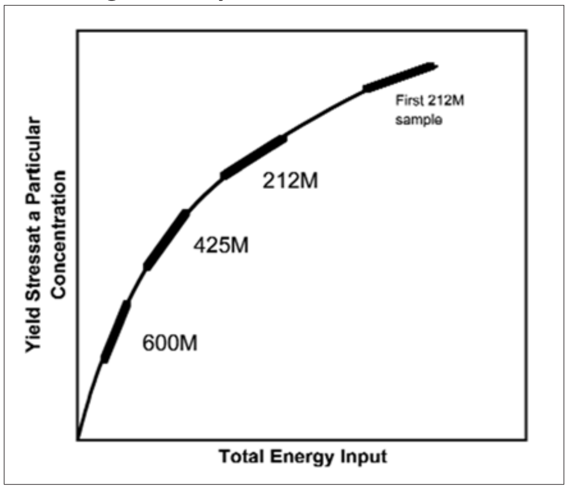
The results are shown in Figure 5 in terms of a ratio increase in yield stress versus unit energy input. The d_{99} 600 micron slurry exhibits the largest increase, with the d_{99} 425 micron slurry the next largest. The smallest increases occurred with the first d_{99} 212 micron sample, which had previously been agitated during storage. The increase in plastic viscosity during agitation is much less than for yield stress. For example, whereas the d_{99} 425 micron slurry yield stress increased by a ratio 4.09 after 90 minutes agitation, the plastic viscosity only increased 1.3 times.

Figure 5. Increase in yield stress with agitation

The higher ratios for d_{99} 425 micron and d_{99} 600 micron may be partly explained due to the attrition which occurs during agitation (4% increase in minus 45 micron for the d_{99} 600 micron sample and 2% increase for the d_{99} 425 micron sample). However, analysis suggests that these relatively small increases in fines do not fully explain the ratio increase differences illustrated in Figure 5. Reduction in particle size also does not explain the observed reduction in yield stress over time in the quiescent state after agitation, discussed later in relation to Figure 7.

In the present paper the viscosity increase with agitation is assumed to be related to energy input during the shearing process. The ratio increase differences in Figure 5 can be explained by considering a total energy input curve as shown schematically in Figure 6. Energy input during grinding contributes to the increase in yield stress, in addition to the energy input during agitation or pumping. The straight lines shown in Figure 6 represent the energy input during 90 minutes agitation in the laboratory mixer. This energy input is similar for all samples (4.3 kWh/m^3). The d_{99} 600 micron sample has been subjected to the least grinding and so is lowest on the total energy curve, at the greatest slope. The d_{99} 212 micron sample has had the most grinding energy input and is towards the top of the energy curve at a lower slope. The first d_{99} 212 micron sample had a lot of additional energy input from the extended period of agitation and recirculation and is furthermost out on the energy curve at the lowest slope.

The physical reasons for the increase in viscosity with agitation is not fully understood at present. It is possibly associated with realignment of clay particles which are known to be present in the Marlborough ores. It may also be partially explained by the presence of a small amount of goethite which has a fibre-like crystal structure. When slurries of goethite, ores are subjected to high rates of shear the goethite crystals become



‘tangled’ causing an increase in viscosity. The increase in yield stress can be reversed by

Figure 6. Schematic total energy curve

gentle shearing (Lussiez and Reid, 1977). The observed reduction in yield stress in the quiescant state may be the result of slow disentanglement of goethite crystals or realignment of clay particles, possibly driven by Brownian motion.

Wheelstand test

Slurry tested and description of Wheelstand

Based on the results of the laboratory-scale rheology tests on d_{99} 212, 425 and 600 micron slurries a pipeline hydraulic analysis was completed. Following consideration of factors such as solids concentration, pumping velocities, pump pressure and pipe wear, the d_{99} 425 micron slurry was selected for testing in the Wheelstand.

Slurry Systems' Wheelstand test rig consists of 200 NB steel pipe, bent into a circular shape to form a wheel supported by spokes. The wheel rotates in the vertical plane about a horizontal axis, driven by a variable speed motor. The diameter of the wheel at the pipe centreline is 2.685 m and the pipe internal diameter is 206.3 mm. The rig is half filled (141 litres) with the required slurry mixture and then rotated at a speed (up to 3 m/s) such that the velocity at the outer inside surface of the pipe is equal to the required pipeline velocity. During rotation the slurry remains in the lower half of the wheel with the pipe moving relative to it. This simulates the relative motion in a pipeline. The Wheelstand has an advantage over a recirculating test loop since the slurry is not subjected to repeated passage through a pump. The wheel is rotated for a period equal to the time needed to transit the selected pipeline length. Changes in slurry properties are monitored by regular removal of 300 ml slurry samples, which are then subjected to laboratory rheology and other tests.

An indication of steel pipe wear and/or corrosion is provided by two Corrosometer probes. One probe element is mounted flush with the outer inside surface of the pipe simulating metal loss rate at the bottom of the pipe. The other probe is mounted 30° from the top invert of the pipe simulating metal loss rate near the top of the pipe. In the current tests the measured corrosion rate was 4.6 to 4.9 mm/y, which is extremely high and not unexpected with saline water slurry. The Corrosometer probes were removed after 4.5 hours since it was apparent that the pipeline would need to be lined.

The slurry solids concentration at the start of the Wheelstand test was 30.55%. The Wheelstand is completely sealed when running. The concentration had increased to 31.14% at the end of the test possibly due to evaporative losses when taking 300 ml samples for rheology determination. At the end of the test the slurry temperature was 34°C compared with the ambient temperature of 26°C. The raised temperature of the slurry would encourage evaporation during sample collection. Sampling error could also explain the increase in concentration. Whatever the reason, the small increase in concentration does not significantly affect the conclusions from the Wheelstand test.

A total of 19 rheology samples was taken during the test. The rotational speed of the Wheelstand was 17.6 rpm, giving a centreline velocity of 2.47 m/s. This isapproximately 10% higher than the final selected velocity in the pipeline. Analysis of viscosity changes is based on distance travelled. The transit time in the pipeline will be approximately 23 hours, which is equivalent to 20.8 hours in the Wheelstand test. The

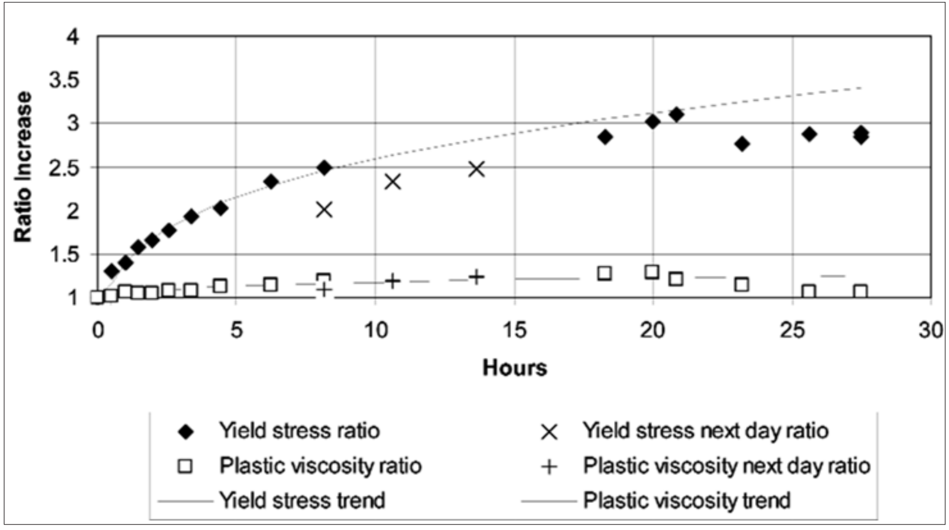
Wheelstand test was run for a total 27.5 hours. Particle sizings indicated a slight increase in the proportion of the minus 45 micron fraction, from 53.27% at the start to 55.15% at the end.

Viscosity changes during Wheelstand test

The slurry viscosity at the start of the test was:

C_w = 30.55%, yield stress = 2.93 Pa, plastic viscosity = 7.48 mPas

and after 23 hours: C_w = 31.14%, yield stress = 9.02 Pa, plastic viscosity = 8.57 mPas. Figure 7 shows the increase in yield stress and plastic viscosity during the Wheelstand test. The measured values have been adjusted for the slight increase in concentration during the test so as to indicate the ratio increases if the concentration had remained constant during the test. Thus, whereas the measured yield stress of the final sample (9.08 Pa) indicates a ratio increase of 9.08/2.93 = 3.10, the adjusted ratio in Figure 7 is 2.85.



During the test the Wheelstand was run continuously except for stops to remove samples, which typically took about one minute. For the majority of samples the viscosity of the sample was measured immediately after collection. However, for two samples (10.6 hours and 13.6 hours) the viscosity was not measured until about 8 hours after collection. The yield stress of these two samples, shown as crosses in Figure 7, is lower than the trend of the other data. As a check the viscosity of the 8.17 hour sample was measured both immediately after collection and also the next day. The 8.17 hour sample comparison confirms that the yield stress decreases with time in the quiescent state.

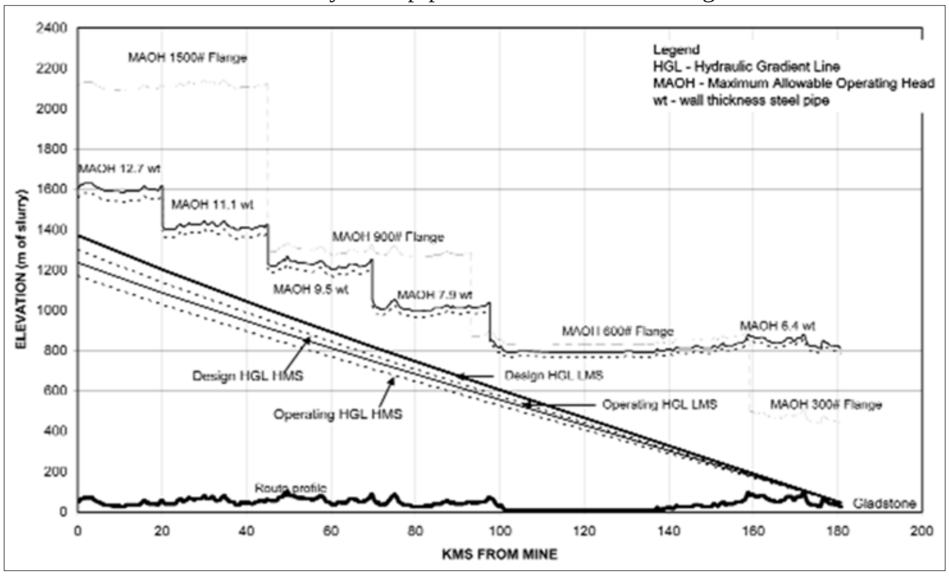
Figure 7. Increase in yield stress and plastic viscosity during Wheelstand test

The ratio increase in yield stress during the Wheelstand test shown in Figure 7 can be compared with the increase during the laboratory agitation tests (Figure 5). The comparison indicates the yield stress ratio increase during the Wheelstand test is approximately 75% of the increase in the laboratory agitation tests. It is considered that the Wheelstand more closely simulates conditions in the pipeline than the laboratory scale agitation test and the Wheelstand ratio increases in yield stress and plastic viscosity have been used for preliminary pipeline design.

Preliminary pipeline design

System description

The 180 km buried pipeline is designed to transport 3 Mtpa of LMS ore and 1 Mtpa of HMS ore as saline water slurry. The pipeline is constructed using DN500 API 5L X70



Grade steel pipe of wall thicknesses ranging from 12.7 mm to 6.4 mm. A 12.3 mm HDPE liner is inserted during construction with flanged joints every 750 m. Flanges range from ANSI Class 1500 to Class 300. The pipe ID ranges from 458 mm at the start to 470.6 mm at the end. The normal operating flow rate is 1 325 m^3/h, resulting in operating velocities ranging from 2.234 m/s at the start to 2.116 m/s at the end. Design flow rates and velocities are 6% higher. The LMS ore is pumped at 29% concentration and the HMS ore at 33% concentration. Figure 8 shows the design and operating hydraulic gradient line and indicates steel pipe wall thickness changes and flange class changes.

Figure 8. Hydraulic gradient line DN500 sea water slurry pipeline

The design pump pressure is 16.36 MPa when pumping LMS ore and 15.95 MPa when pumping HMS ore. Six positive displacement piston diaphragm pumps are installed in parallel. Five pumps operate with one standby spare. Each pump is driven by
1 850 kW variable speed motor.

Design considerations

The fundamental aim of the design is to transport the nickel laterite ore as efficiently as possible. This means pumping at as high a solids, concentration as possible consistent with maintaining turbulent flow whilst avoiding excessive velocities. The rheological investigations into d_{99} 212, 425 and 600 micron slurries were considered. The d_{99} 425 micron top size was selected as representing a compromise between the reduced slurry viscosity and the increased heterogeneous effects which occur as the particle size increases. Similarly, the relatively high velocity compared with most long distance slurry pipelines allows for the coarser particle size and also enables a higher transition velocity and hence concentration to be accommodated.

The velocities and concentrations are selected so that turbulent flow is maintained throughout the pipeline despite the yield stress increase along the pipeline causing the laminar-turbulent transition velocity to increase. There is a direct relationship between yield stress and the transition velocity (Wilson and Thomas, 2006). The plastic viscosity increases along the pipeline and this would normally result in an increase in friction loss. However, as shown in Figure 7, the yield stress increases by a greater amount. Non-Newtonian effects due to the greater yield stress would result in a slight decrease in turbulent head loss gradient along the pipeline if the pipe diameter remained constant (Wilson and Thomas, 1985). The increase in pipe internal diameter and reduction in velocity as the wall thickness reduces along the pipeline result in a more significant reduction in head loss gradient.

The LMS and HMS slurries are to be transported in batches, typically 18 hours pumping LMS ore then 6 hours pumping HMS ore. No saline water slug is inserted between the batches and an analysis of interfacial mixing between the batches based on
99% purity of LMS at one end and 99% purity HMS at the other end predicts a mixing length of 650 m equivalent to 113 m^3 volume or 5 minutes of flow.

The yield stress reduces when the slurry is in the quiescent state after agitation ceases. This is illustrated in Figure 7 and was generally observed. This means that if the pipeline is shut down full of slurry the yield stress will decrease during the shutdown meaning that restart pressures will be less than otherwise would have been the case.

It is illustrated in Figure 3 how agitation and pump recirculation for 70 hours resulted in the yield stress of a d_{99} 212 micron slurry increasing by more than three times. To minimize this phenomenon in the final plant it is envisaged that the agitators in the pump station storage tanks will normally be switched on only just prior to pumping.

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