The Pumping Characteristics and Rheology of Paste Fills

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Synopsis
The paper discusses the transport and rheological characteristics of high concentration slurries or pastes for backfill purposes. The influence of pipe size, particle size distribution, additives, coarse material and mass concentration on these characteristics is addressed.

Introduction
The gold mining industry in South Africa produces two main waste products, namely a silt-sized rock flour, otherwise known as reduction plant tailings (RPT), or slimes, and a crushed development waste rock (CDW).

As the mines have become deeper and the cost of ventilation has increased alternative methods for support and fill have been investigated. One of the techniques has been the hydraulic filling of stopes in deep mines with pumped waste materials. This method has proved itself to be a means of limiting the convergence of the stopes, absorbing energy released from the surrounding rock and increasing the percentage extraction of gold from wide reefs.

There are a number of hydraulic backfilling techniques, each of which appears to have its particular niche in the industry. This paper discusses the transport characteristics of high concentration slurries, or pastes, for backfill purposes as well as some of the research findings of institutions such as the University of the Witwatersrand Technology Centre, the CSIR and the mines involved in this research.

Characteristics of a paste
Slurries on a headloss versus velocity diagram (Figure 1) can generally be classified into several flow regimes. These different regimes can to a certain extent be distinguished according to particle size and specific gravity whereby small particles are transported in the homogeneous zone and coarser particles in the heterogeneous zone.

However, in a conventional dilute slurry where the volumetric concentration is less than 50%, individual particles will be free to settle. Generally, the extent to which they will do so in horizontal flow depends upon the relative
extent of the gravitational settling velocity, the turbulence within the liquid tending to support the particles and the particle-particle interaction.

As the volumetric concentration increases above 50% the particles are no longer free to settle, and the flow within the pipe changes to that of plug-flow, with the extreme case illustrated in Figure 2.

A typical viscosity and density relationship for a mixture of solids and liquid is illustrated in Figure 3. The higher viscosities and densities prevalent in the paste regime result in hindered settling velocities and high pressure gradients. This hindered settling velocity allows pastes to be transported in the range of $0.1 - 1.0 \, \text{m/s}$ as opposed to the conventional slurry transportation velocities of $1.0 - 5.0 \, \text{m/s}$.

The high pressure gradients within the pipeline generally necessitate the use of positive displacement pumps. The velocity profile of a typical Bingham-type paste is illustrated in Figure 4. The central core moves at a constant velocity, while the velocity profile around the plug will vary relative to the viscosity and shear stress prevalent in the annulus.

Not all materials can be transported in a paste form but those that can form highly stable pastes.

**Application of paste technology to backfilling**

There are two main approaches to paste filling. The first utilizes only the reduction plant tailings while the second incorporates the crushed development waste in the RPT carrier to form the paste.

**Reduction plant tailings**

RPT varies in size distribution and specific gravity from mine to mine. Figure
Figure 2. Pipeline transportation of paste.

The solids concentration for long-distance conveying in gold mines varies within a range up to 62% by mass whereas for paste backfilling the concentration range can go as high as 78%. Maximum concentration is dependent on the particle size range of the material being pumped, the pump feeder and the pressure resistance in the pipeline.

Research by Sauermann (1982) and Verkerk (1982) has shown that once the solids concentrations exceed 50% by mass, and flow is in the laminar zone, any further increases in mass concentration result in large increases in pressure gradient. Such increases limit the maximum pumping distance. Sauermann (1982) showed that for slurries with concentrations up to 64% the general trend shown was one of decreasing pressure gradient with increasing $d_{50}$. 
Figure 3. Viscosity and density relationships.

Figure 4. Velocity profile of a high concentration paste.
Figure 5. Reduction plant tailings distributions.
Figure 6 illustrates the changes in pressure gradient for a slimes product with a $d_{50} = 45 \mu m$ in a 200 mm pipeline. A laminar behaviour was observed at a mass concentration of about 60%. At $C_w = 65\%$ the pressure gradient is approximately double that of the $C_w = 60\%$ slurry in the laminar zone. A further increase in solids concentration of 2.5% increases the pressure gradient a further two and a half times.
Increasing the concentration even higher \( (d_{50} = 18 \, \mu m) \) results in still higher pressure gradients (Figure 7).

From these results it was concluded that RPT slurries with a \( d_{50} \) of between 25 and 50 \( \mu m \) can be transported in the laminar flow region at mass concentrations of 50% and greater. Care should be exercised, however, when transporting these fine slurries in the laminar zone as the larger particles still have a tendency to deposit in the pipe which can result in unstable pumping conditions.

The exceptions to this deposition (Wasp, 1977) are materials which are transported at concentrations close to compaction. Compaction in this case refers to a situation where negligible internal settling occurs within the slurry. This can be achieved with some gold slimes where the solids concentration is increased to \( 70 - 78\% \).

Figure 6 illustrates that the slimes slurry, at a mass concentration of 67.7\%, is transported close to compaction in the laminar zone and at a velocity lower than the transition value. However, in the case of lower concentrations and coarser slimes it is recommended that the slimes be transported at a velocity higher than the transition value.

A standard procedure recommended for some mines is the dewatering and desliming of the feed supply which arrives in the region of \( C_w = 62\% \) prior to placement as a paste of \( C_w = 70 - 78\% \). Dewatering with cyclones removes the super-fines \((-25 \, \mu m)\); this activity is important when trying to create a 'non-bleeding' backfill mix. A non-bleeding characteristic is important in preventing the water being transported through the coarser materials where the paste is pumped at a high pressure or when the pipeline is restarted. A cycloned slimes paste with the addition of a super-fine binder such as
Figure 8 illustrates size distributions of two slimes pastes which can be pumped (samples 1 & 2) under all conditions, and one which blocked the pipe (sample 3) when transported at high pressures, or was left stationary in the pipe for a while. The high pressure gradients in the laminar flow region can be reduced through the addition of ‘viscosity modifiers’ by adding CDW to the paste or by using large pipe diameters.

Work done by Horsley (1982) indicated that the addition of sodium tripolyphosphate (Na₃P₅O₁₀) reduces the pressure gradients. Figure 6 illustrates how the addition of 0.2 kg/t Na₃P₅O₁₀ to a Cₜ = 67.7% slurry reduced the pressure gradient by 30% in the laminar flow zone. The addition of 0.5 kg/t reduced the pressure gradient by 70% while with 1 kg/t the laminar flow region almost disappears; with an additive of 1.5 kg/t the slurry is transported in the turbulent region at a velocity of 1.1 m/s.

It is interesting to note that the turbulent regions of the curves with and without the additive coincide. This indicates that the additive, rather than changing the absolute viscosity value, is responsible for breaking down the initial yield stress of the slurry. This effect is shown in Figure 9 where with various additives and neutralizers the yield stress is changed while the absolute viscosity value remains virtually unchanged. The viscosity in this case is taken as the slope of the flow curve while the yield stress is equivalent to the intercept of the curve, on the y axis of the rheogram.

Although the Na₃P₅O₁₀ was found to affect the yield stress of the slimes tested, the same effect does not occur with all slimes, where in some cases polymers have been found to modify the yield stress. The effect of the change of the yield stress is apparent if one considers a generalized Moody diagram for a Bingham plastic (Figure 10). The decreasing yield stress values result in lower Hedstrom numbers and consequently lower friction factors for the same Reynolds numbers in the laminar zone.
One possible disadvantage of the use of additives is that prior to placement in the stopes the effect of the additive needs to be neutralized so that normal strength and energy absorption characteristics of the fill are regained. In some cases the additive decays naturally over a period of time while in other cases specific neutralizers have to be added.

**Crushed development waste**

The second alternative for decreasing pressure gradients while at the same time increasing the strength characteristics of the fill is by adding coarse material or CDW. Tests carried out by Verkerk and Macur (1982/3) included varying the ratio of slimes to CDW from 20:80 to 60:40. In these tests the maximum size of the waste rock was limited to 27 mm. This was dictated by the size of the test pipeline (120 mm). Further testwork in this area has also been carried out by Mohlman (1986).

Generally, the maximum aggregate size should be limited to 30–40% of the inner conveying line diameter, although single particles with diameters up to 60% of the pipe diameter should not cause problems.

A further limitation to the inclusion of the CDW in the RPT paste is the control over the total size distribution. It is necessary that the size grada-
Figure 10: Moody diagram for a Bingham plastic.
tion for each particle maximum size falls within the correct envelope (Figure 11). The standard German DIN 1045 curves for the pumping of concrete provide a useful guide. Higher fines contents when transporting a 50:50 ratio of RPT:CDW does however allow for deviations outside the pumping envelope (Figure 11).

The water-to-slimes ratio also must be controlled. Table 1 indicates how for different concentrations of the slimes-carrying medium and different CDW-to-RPT ratios the paste can be rendered virtually unpumpable.

The concentration of the overall mixture can be influenced by the CDW aggregate and the $C_w$ of the RPT. Coarser, larger sized CDW requires less fines while CDW with a low percentage of the sand component needs a thicker RPT to reduce segregation on the mixture. A standard slump of 200 mm generally provides a pumpable mix with reasonable pressure gradients. More liquid mixtures tend to segregate while drier mixtures create extremely high

Table 1
Pump results with slimes-rock mixtures

<table>
<thead>
<tr>
<th>Ratio of CDW:RPT</th>
<th>Mixture: water content by mass (%)</th>
<th>RPT only: water content (%)</th>
<th>Slump test on 300 mm cone (mm slump)</th>
<th>Pipeline pressure drop in a 125 mm pipeline (kPa/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50:50</td>
<td>20</td>
<td>40</td>
<td>260</td>
<td>13</td>
</tr>
<tr>
<td>67:33</td>
<td>136</td>
<td>40</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>51:49</td>
<td>13</td>
<td>25.5</td>
<td>155</td>
<td>20</td>
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<td>60:40</td>
<td>12</td>
<td>27.5</td>
<td>55</td>
<td>34</td>
</tr>
<tr>
<td>60:40</td>
<td>10</td>
<td>22.2</td>
<td>50</td>
<td>37.3</td>
</tr>
</tbody>
</table>
With the addition of coarse aggregates the overall mass concentration (for similar pressure gradient) is higher than that of the pure RPT paste. The maximum concentration recorded during the testwork was 87.1%. This was achieved with a 20:80 RPT:CDW mixture.

A comparison between the pressure gradient of a pure RPT paste with a RPT:CDW paste with a higher $C_w$ is illustrated in Figure 7. The reduction in pressure gradient is due to the decreased wetting area presented by the larger particles leaving more water which forms a less dense carrying medium. The lower density carrier (relative to the overall mixture) in which the larger particles rest thus has a lower viscosity and consequently a lower friction factor, as is illustrated in Figure 10.

Although, from a pumping point of view, a 50:50 mixture appears to offer the best characteristics, the final formulation of the fill depends upon the availability of the constituents, the required strength and energy absorption characteristics, the conveying distance, the pumps available and the cost-effectiveness of the backfill operation.

**Increasing the pipe diameter**

A third alternative for reducing pressure gradients is by increasing the pipe diameter. This effect is illustrated in Figure 12 (Ede, 1957) for a concrete mixture being transported through various pipe diameters. As the pastes, either a pure RPT paste or a mixture of CDW and RPT, are inherently stable and can be transported at low transport velocity, this diameter effect can be used to good advantage.
Conclusion
From the increased interest in paste hydraulic backfill techniques in South Africa it is evident that the benefits of hydraulic transportation of high concentration slurries are being recognized. With the correct selection of waste material it is possible to produce a cost-effective fill that satisfies the requirements of each particular mine where this method is applied.

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Nomenclature

\[ C_w = \text{concentration by mass} \]

\[ d_{50} = \text{diameter of the sieve aperture through which 50\% of the sample by mass is retained} \]

\[ r_o = \text{radius of plug} \]

\[ \rho = \text{density} \]

\[ \Gamma_w = \text{wall stress} \]

\[ \Gamma'_o = \text{yield stress} \]

\[ \mu = \text{viscosity} \]

References
VERKERK, C.G. An investigation into the transportation of low and high concentration slurries. MSc dissertation, Faculty of Engineering, University of the Witwatersrand, Johannesburg, 1982.