Pipelining Tailings, Pastes and Backfill

L. Pullum *Consulting Engineer, Australia*

ABSTRACT

This paper reviews recent research into the pipelining of high concentration suspensions such as pastes and backfill materials. In recent years, insight into the flow of these materials has been gained which shows the stratification of apparently homogenous suspensions when sheared. Because of this, these suspensions must be considered as two distinct phases, a carrier fluid and course burden. Various hydraulic flow regimes involving these distinct phases are discussed and mechanistic models proffered. Homogenous pipe flow is shown to be only one of several flow regimes.

1 INTRODUCTION

With the exception of a few sites on steep leases where launders can be used, the disposal of tailings invariably requires hydraulic transport of the solids through pipes from the plant to the impoundment area, or disposal site. If one considers tailings, inter-process transfers and freight products, the amount of material that is conveyed by pipeline each year is staggering. Despite this ubiquity, however, pipeline transport is still treated with suspicion and remains a dark art to many, including some practitioners and the author. Flow behaviour is the result of complex interactions between fluid dynamics, rheology and particles science, and can range from the simple laminar flow of homogenous materials through turbulent suspension flows to granular flows, where the solids are conveyed as a packed bed. This paper will examine the range of flow regimes, linking them to the various modes of tailings disposal and report on some of the recent insights that modern instrumentation and computational power have provided for flow regimes particularly suited for paste and backfill transport.

2 HISTORY

Hydraulic conveying, as an engineering solution to solids transport, has been performed since the middle of the 19th century. For example, in London it was used to unload coal from barges in the Thames and transport it via an underwater pipeline to Battersea power station, close to the Houses of Parliament. This lump coal was pumped as a low concentration heterogeneous suspension in water, an inherently unstable mode of transport, which eventually blocked the pipeline, and I believe it remains blocked to this day. It is perhaps this public, less than auspicious, start to a technology and the surprisingly complex nature of the many flow regimes, that has slowed down the acceptance of new modes of hydraulic transport and ensured that a very conservative approach be adopted. This is especially true for low value products such as waste streams. Conventional tailings disposal since that time has typically involved pumping very low concentrations of solids to large catchments. Here the solids rapidly settle, forming a denser bed, while the conveying water is either returned to the plant or simply left to evaporate off. This mode of transport is relatively simple, as low concentrations of small particles are unlikely to block pipes and the transport characteristics, not surprisingly, are similar to turbulent pipe flow. This form of tailings disposal, however, is generally no longer acceptable in the 21st century, where environmental and economic imperatives prevent the construction of such large tailings dams, or allow such low concentration suspensions to be used.

The result of these imperatives has been to increase the solids concentration of the suspension delivered to the tailings dams. This increase, however, dramatically changes the behaviour of the pipelines, as particle-particle interaction starts to dominate the flows and the suspensions no longer behave like simple turbulent pipe flows. In some lines, the minimum velocities that must be maintained to prevent pipeline blockages increase, while in others the reverse occurs, the line becomes easier to operate, but the solids separation in the dam becomes profoundly worse. In both cases, the transport pressure gradients increase and this combined with the reduction in solids separation at the end of the line results in a severely de-rated disposal system.

Since the latter half of the 20th century it has been obvious that a paradigm shift was required and new forms of waste disposal were proposed (e.g. see Robinsky, 1968; Nguyen and Boger, 1998). Now, rather than pumping the material out to the dam at low concentrations and allowing settling and evaporation to concentrate the deposit, it was proposed that the tailings be thickened, in advance, to this final concentration (or a higher one) and then pumped out to the impoundment area. Thickened discharge systems had the advantage that they required a much smaller footprint than conventional dams and could be built on flat planes, as the valley or high dam walls required to contain the excess fluid were no longer necessary. In parallel with this, thickener technology was progressing and the advent of deep cone thickeners producing high concentration pastes became available. Pipelining, too, was experiencing a change in direction. Conventional, low concentration conveying systems, typical of long distance freight pipelines and inter-plant transfers, use a technology that attained maturity in the middle of the last century. This technology ensures that finely ground particles can be conveyed at low pressure gradients, allowing pumping stations to be spaced considerable distances apart. Freight pipelines can consequently span large distances, i.e. 100's of kilometres. Large or dense particles conveyed in this manner, however, require high velocities and concomitantly high pressure gradients, preventing them from being conveyed economically over long distances by pipeline. Attempts to address this problem produced a considerable amount of research around the world during the '70s and '80s (Lawler et al., 1978; Thomas, 1978; Duckworth et al., 1982; Brookes and Snoek, 1986; Brown, 1988; Hore et al., 1990) and a form of transport commonly called "Stab-flo" resulted. Despite the coarse particle content, such materials flow very easily and this technique allows coarse particles to be conveyed under ostensibly laminar flow, at low velocities, without fear of blocking the pipe. However, while specific energy consumption values were low, they were not as low as that for conventional fine particle transport and the method was abandoned for use in long distance transport (Thomas et al., 2004). It is interesting to note that these types of suspensions are now being reinvented as capping materials (Wilson et al., 2006).

An alternative approach to conveying coarse particles at lower velocities and lower specific energy consumptions was simply to increase the solids concentration up to values approaching the packed bed concentration (Brown et al., 1979; Bhattacharya and Imrie, 1986). These ultra high concentration (UHC) flows can similarly be run under ostensibly laminar flow at low velocities, and, providing the high solids concentrations is maintained, without fear of blocking the pipe. Again, however, the pressure gradients were considered too high for long distance transport.

For the relatively short distances, i.e. tens of kilometres, required for tailings disposal, or backfill operation, the pressure gradient is no longer the overarching constraint. Instead, minimising the size of the deposit, minimising water consumption, improving deposit stability, increasing drainage and reducing chemical species mobility are more important criteria. These newer pipelining techniques are thus in keeping with these goals.

3 FLOW REGIMES

Paste and backfill suspensions are typically characterised by a stable, homogenous appearance and have a low slump, i.e. they have a substantial internal structure. In contrast, conventional tailings materials are made of a watery, gritty slurry that usually rapidly settles out of suspension. The transport characteristics of these materials are, not unexpectedly, very different.

Because of their homogenous appearance, pastes are usually assumed to behave homogenously in the pipe. For very fine particles, i.e. < 20 μm, at high enough concentrations, the particles may form a truly homogenous paste material. Such materials, e.g. red mud, are invariably non-Newtonian and may be described using various constitutive equations or rheological models (Hart and Boger, 2005; Jewell and Fourie, 2005; Sofra, 2006). However, many pastes and particularly co-disposal systems have particles that are larger than this and a simple homogenous analysis is insufficient to describe their behaviour. Backfill suspensions are generally designed to have insufficient fine particles to form a non-Newtonian fluid, as this impedes drainage and so these too cannot be successfully described as homogenous materials. To understand paste flows it is therefore necessary to examine more flow regimes than simple homogenous flow.

3.1 Traditional Tailings Lines

As mentioned previously, traditional tailings lines are relatively low concentration ($c_v < 40\%$ v/v), turbulent, water based systems, where the mode of transport is through interaction between the solids and turbulent eddies within the pipe. Typical transport characteristics are shown in Figure 1.

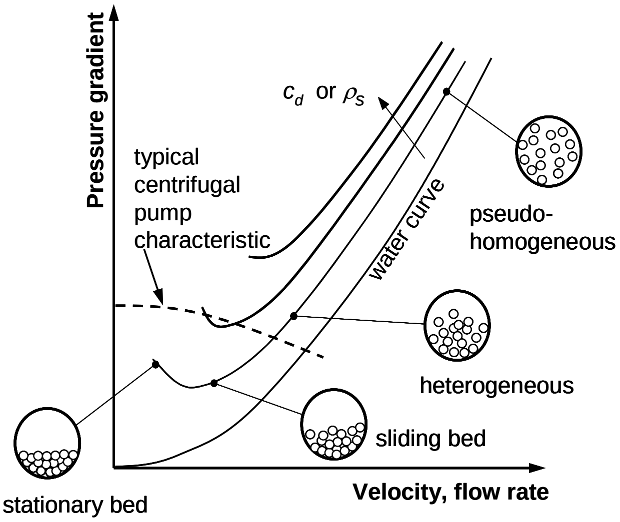


Figure 1 Traditional tailings line transport characteristics

At high enough velocities, the turbulence level is so great that particles are randomly lifted across the entire pipe cross section and a pseudo-homogenous suspension is obtained. The excess pressure gradient for a given velocity, above that for the fluid alone, is approximately equal to the increase from the fluid density to the suspension density. As the velocity reduces, the strength of the turbulent eddies diminishes and the solids are not supported so energetically. The ability for the particles to be lifted across the entire pipe diameter reduces, a concentration gradient develops across the pipe and particle wall interaction increases. At lower velocities, the particles become confined to the lower half of the pipe forming a bed, and increased particle/wall interactions result in a greater excess pressure gradient than before. At this point, the solids are transported primarily by the drag of fluid flowing over the bed and through the pressure gradient applied across it. The fluid is now flowing substantially faster than the solids and so the local in-line concentration increases to maintain continuity. This in turn increases the excess pressure forming a characteristic hook curve, as shown. Eventually, as the flow reduces even more, a point is reached where the combined drag and pressure forces are insufficient to overcome the frictional restive forces and the solids stop moving. Thus, a minimum transport velocity is required to ensure the movement of the bed and usually an even higher velocity is required to lift the solids clear of the lower pipe wall. Increasing either the particle size, particle density or solid’s concentration will exacerbate this behaviour, as shown. Stable operation requires that the suspension characteristic crosses the pump curve (shown dashed) with a substantial angle and preferably orthogonally. Therefore, when using centrifugal pumps, operation at velocities lower than the minima in the characteristic is unstable and so a higher “operational” minimum transport velocity is set at some point to the right of the minima shown.

3.2 Homogenous Flows – Very Fine Pastes

If the particles are very fine (say < 20 μm) and the particles are rheologically active, inter-particle forces may be sufficiently high to overcome other fluid-dynamic and body forces, so that the suspension, or slurry, behaves as if it were a single phase fluid. Alternatively, flocculent may be used when thickening and this acts to bind the particles together to form a homogenous flocculated suspension. The strength of these inter-particle forces is a strong function of solids concentration, particle size, surface chemistry, temperature, ionic content and pH. The resulting slurry may be sensitive to shear history so that the materials structure may be temporarily weaker after shearing (thixotropy), or so sensitive to the degree of shearing that excessive shearing can destroy or permanently weaken these bonds. Slurries found in the mineral processing and mining industries are generally visco-plastic, thixotropic materials with characteristics similar to those shown in Figure 2. The materials may also be visco-elastic, especially if flocculants have been used, but generally speaking this only affects the detailed nature of turbulent flows and are beyond the scope of this review.

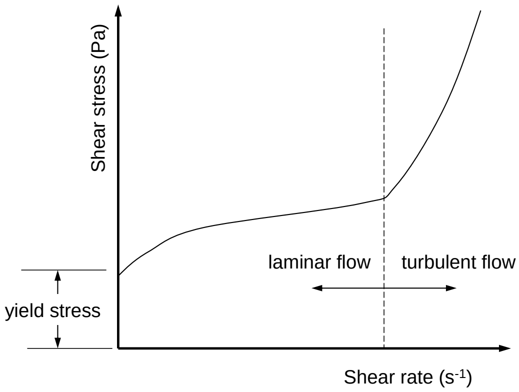


Figure 2 **Typical shear thinning behaviour of homogenous slurries found in the mineral and mining industries**

Unlike a Newtonian fluid, which would have a linear relationship between shear rate and shear stress and consequently a constant viscosity, the relationship between shear rate and shear stress for visco-plastic fluids is not constant and therefore, neither is the viscosity. Instead, the viscosity becomes a function of the applied shear rate (or applied shear stress). The laminar part of the curve shown in Figure 2 is concave, so that the gradient for the curve decreases with shear rate. These fluids are known as shear thinning fluids, as the viscosity, defined at any shear rate as the ratio of shear rate/shear stress, decreases with shear rate. The fluid also exhibits a minimum stress that must be applied before the fluid will flow, this is called the yield stress. At higher shear rates, or more correctly higher Reynolds numbers, the flow becomes turbulent as shown.

The yield stress may be measured in a variety of ways. A rheogram, such as that shown in Figure 2, can be produced using a suitable viscometer and a value inferred by projecting the curve so that it intersects the shear stress axis. Alternatively, a vane can be inserted into a container of fluid and a rotational torque applied until the fluid yields (Nguyen and Boger, 1992), or an approximate value can simply be inferred from a slump test (Pahias and Boger, 1996). The values obtained by these different methods will, unfortunately, be different. If the slurry is thixotropic, the yield stress will be a function of the shear history. In the first method, the yield stress is obtained by shearing the fluid to obtain the rheogram, so that the extrapolated yield stress value is for a sheared and, hence, thixotropically broken-down fluid. The degree of thixotropic break-down will depend upon the actual shear history that the sample is exposed to. This extrapolated yield stress is often known as the dynamic yield stress. In the vane method, the material is stationary and only a very small micro-strain imposed before the yield stress is measured. If the sample has not been pre-sheared before testing, this yield stress will be the un-sheared yield stress, often known as the static yield stress. If the sample is pre-sheared and is thixotropic, there is the possibility that the material will at least partially rebuild before testing. In both cases the static yield stress will be greater than the dynamic yield stress. Similar arguments can be raised for static yield stress values obtained from slump tests. Which is the correct value to use? For normal operation of the pipeline the flow is moving, so the dynamic yield stress is the correct value to use in this case. Furthermore, the slurries have normally passed through mixing tanks and one or more centrifugal pumps, or a centrifugal pump and positive displacement pump before entering the pipeline, so that most slurries will be at their most thixotropically broken-down states or equilibrium condition. If, conversely, it is the tailings deposit strength that is of concern, or the ability to re-slurry a deposit, then it is the static yield stress that is the appropriate value to use. The difficulty in establishing a suitable yield stress has lead researchers to question the various methods when applied to pipelining (e.g. Paterson, 2002), and the problem becomes even more difficult when the pastes also contain large, or non-rheologically active, particles as discussed in the next section.

These visco-plastic fluids produce a much blunter laminar velocity profile than Newtonian fluids and have an un-sheared core or plug in the centre of the pipe as shown in Figure 3. In the Newtonian case, the viscosity is constant throughout the pipe and consequently the velocity profile is parabolic. For the shear thinning fluid, however, the viscosity is lowest at the wall, rising to an infinite value at the radial location, where the local shear stress equals the slurries yield stress. Flow at smaller radii cannot occur and so a rigid plug is transported at the maximum velocity in the pipe.

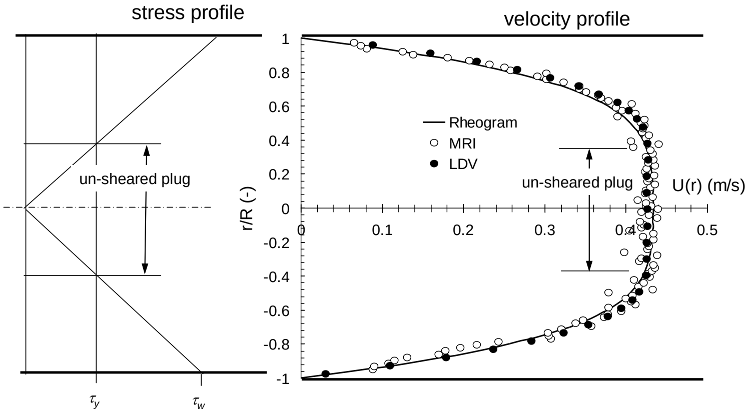


Figure 3 **Visco-plastic velocity profile measured with an LDV and MRI compared to the analytical value obtained from the fluid's rheological properties**

Laminar flow extends until the inertial forces overcome the viscous forces and the flow moves through transitional turbulence into fully turbulent flow. The point at which non-Newtonian flows generally become turbulent is still a subject of research, but various workers (e.g. Slatter and Wasp, 2000) have suggested that the transitional velocity for Bingham plastics is approximated by:

$$V_c = k_1 \sqrt{\frac{\tau_{yB}}{\rho_m}} \tag{1}$$

where τ_{yB} is the Bingham yield stress, ρ_m the slurry density and k_1 a constant; $22.5 < k_1 < 26$. For other rheological models the turbulent transition can be obtained from the intersection of the laminar curve and the calculated turbulent curve (Wilson and Thomas, 1985). Apart from being able to delineate the flow regimes, the transitional velocity is also important because this is the optimal pumping velocity for these flows, in terms of pressure drop and/or energy consumption.

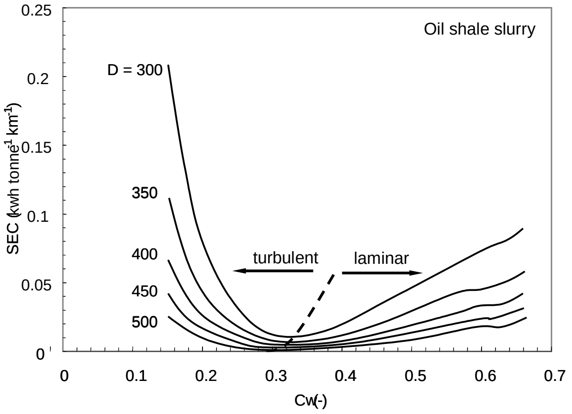


Figure 4 **Typical homogenous slurry specific energy consumption characteristic showing optimal properties at transitional velocities**

Turbulent behaviour of these fluids is superficially similar to Newtonian fluids, but the local variation in viscosity modifies the radial turbulent eddy distribution, effectively trapping the more energetic eddies close to the pipe wall and suppressing the turbulence in the central regions. Direct numerical simulation (DNS) studies performed on super-computers (Rudman et al., 2002; Rudman et al., 2004; Rudman and Blackburn, 2006) have been able to capture this behaviour and the databases these computations have produced are being used to verify non-Newtonian friction factors and other transport related phenomena.

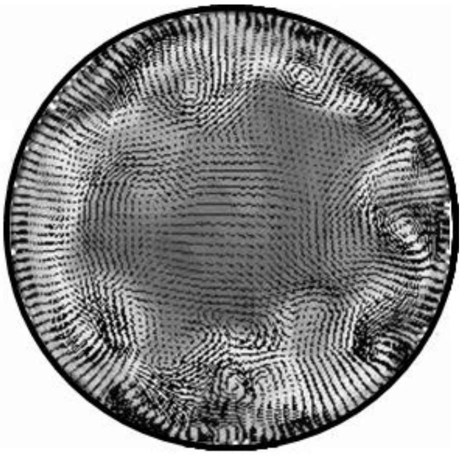


Figure 5 **Example of a DNS simulation of visco-plastic flow in a pipe. Vectors show velocity in the plane of the page, grey scale shows velocity out of the page with the highest velocity in the middle of the pipe**

A snapshot from one of these simulations is shown in Figure 5, where the turbulence levels indicated by the tortuosities of the vector field, are seen to be suppressed in the central core. Unlike in laminar flows, the central core region is sheared for all fluids tested thus far, albeit at a much lower rate than the surrounding annulus. Whether re-laminarisation occurs within the central core for very high yield stress fluids awaits further computational experiments.

3.3 Hybrid Flows – Paste and Co-Disposal Flows

Very few pastes are limited to particle sizes < 20 μm, and most have a substantial portion above this. These "coarse" particles' masses are sufficiently large such that inertial and body forces exceed the various inter-particle forces and they behave as a separate and distinct phase, moving independently to the surrounding slurry, i.e. a suspension of coarse particles in a non-Newtonian slurry, or carrier fluid, made from the finer particles, is formed. This is at odds with the popular perception that the pastes are homogenous. Gross transport characteristics for these paste flows are very similar to homogenous flows (see Figure 6) and when deposits are formed (or taken for slump tests etc.) the fluid does not bleed out and particles do not appear to settle. When the paste undergoes shear, however, the situation changes and settling of these coarse particles can occur (Thomas, 1979; Song and Chiew, 1997; Pullum and Graham, 2000; Cooke, 2002; Wilson et al., 2003; Talmon and Huisman, 2005).

It can be shown (Thomas, 1979; Duckworth et al., 1982) that under static conditions a particle submerged in a visco-plastic fluid will be suspended, providing the yield stress of the fluid exceeds a critical yield stress τ_{yc} given by:

$$\tau_{yc} \geq k_2 g d(\rho_s - \rho_f) \tag{2}$$

where g is the gravitational constant, d the particle diameter, ρ_s and ρ_f the solids and fluid densities respectively and k_2 ,a shape factor, ≈ 0.1 for typical mineral particles. If the particle is placed in a sheared flow, however, the yield stress is no longer available to support the particle and the particle settles through a fluid, with a viscosity determined by the local shear rate, i.e. the second invariant of the local strain tensor. To demonstrate this, consider the laminar transport characteristics of a synthesised co-disposal system, where the fine particle slurry has been replaced with an aqueous polymer gel into which coarse particles have been added, Figure 6.

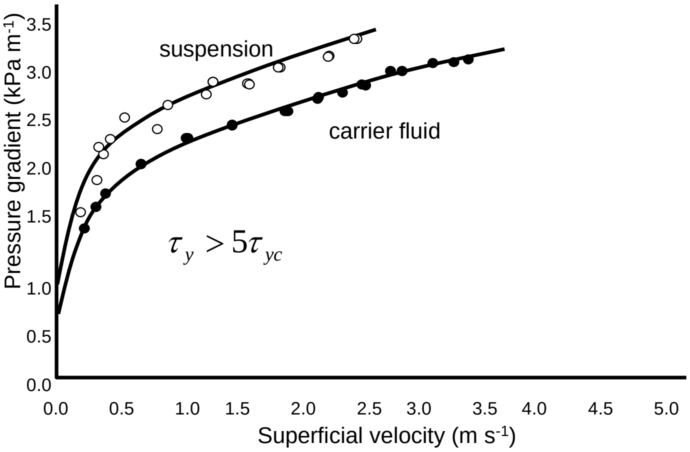


Figure 6 Transport characteristics of a synthetic co-disposal system of sand and Ultrez in a 100 NB pipe

The suspension was designed so that the underlying carrier fluid's yield stress exceeded the critical yield stress, τ_{yc}, by a factor of 5. The suspension was very stable with a sample showing no signs of settling for a period in excess of two years. As shown, the suspension's transport characteristic is very similar to the homogenous carrier fluid's characteristic. Witnesses monitoring the pipeline using conventional instrumentation and visually observing the material entering and leaving the pipe would conclude that the flow was homogenous. However, probing the flow with a MRI and also recording the flow on video through an optical window revealed that the flow was stratified.

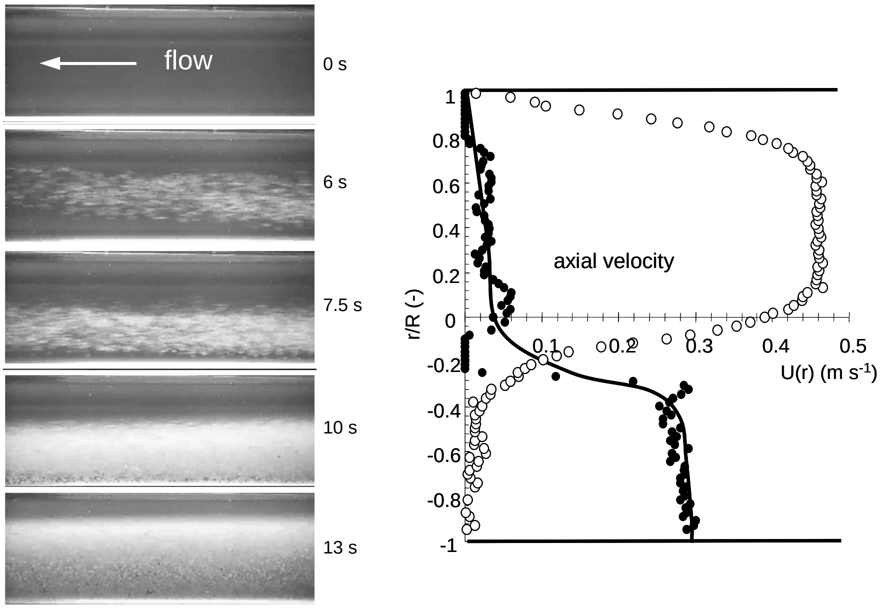


Figure 7 Stills taken from a video sequence demonstrating the particle settling behaviour under shear, and the measured solids concentration and carrier fluid velocity profiles on the vertical diameter of the pipe

For homogenous flows it was shown there is an un-sheared plug in the centre of the pipe. Since this is un-sheared, particles in this region of the pipe should remain suspended. Examination of the stress distribution within the fluid, on the vertical centre line for a stratified flow like this (Figure 8), shows that on this plane the distribution is still linear, but the zero value has been shifted above the pipe centre line to the dynamic centre, i.e. the centre of the velocity profile of the fluid above the bed.

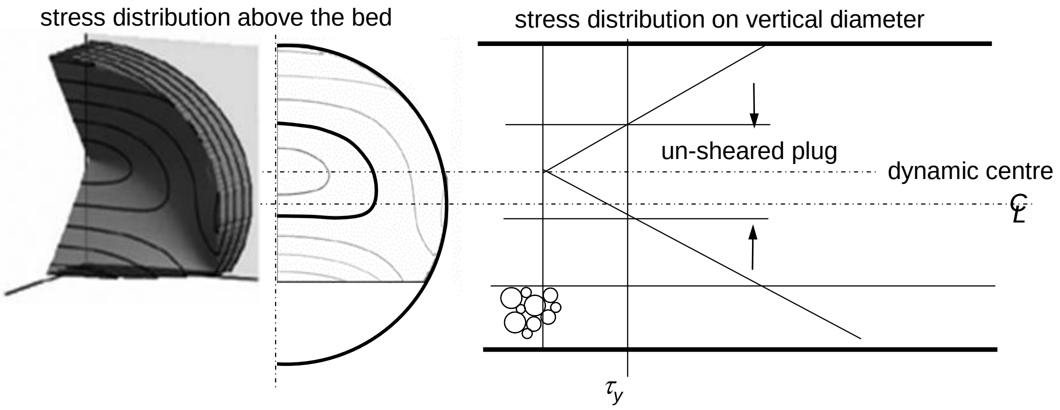


Figure 8 **Stress distribution in the fluid above the bed and on the vertical diameter. The yield stress contour is shown in a heavier line**

For some suspensions, a new separate core containing the original suspended solids can co-exist with the bed shown here, but in most cases the dynamic centre sweeps through the central core as the bed forms, so that all particles in suspension settle as shown in Figure 7.

Stratified flows like these are fundamentally similar to the bed flows described in §3.1 for conventional tailings lines. The main differences here, though, are that the flow is laminar and so turbulent support for the particles is absent. Also, the conveying fluid is non-Newtonian and consequently the properties of the carrier fluid vary spatially within the pipe's cross-section and the minimum conveying velocity is suppressed due to the high viscosity of the carrier fluids. For conventional tailings lines, such stratified flows can be analysed using a sliding bed mode (Wilson, 1976; Shook and Roco, 1991) and similar models have been developed for these non-Newtonian based systems (Pullum et al., 2004a; Pullum et al., 2006), typical predictions using this model for a synthetic co-disposal system are shown in Figure 9.

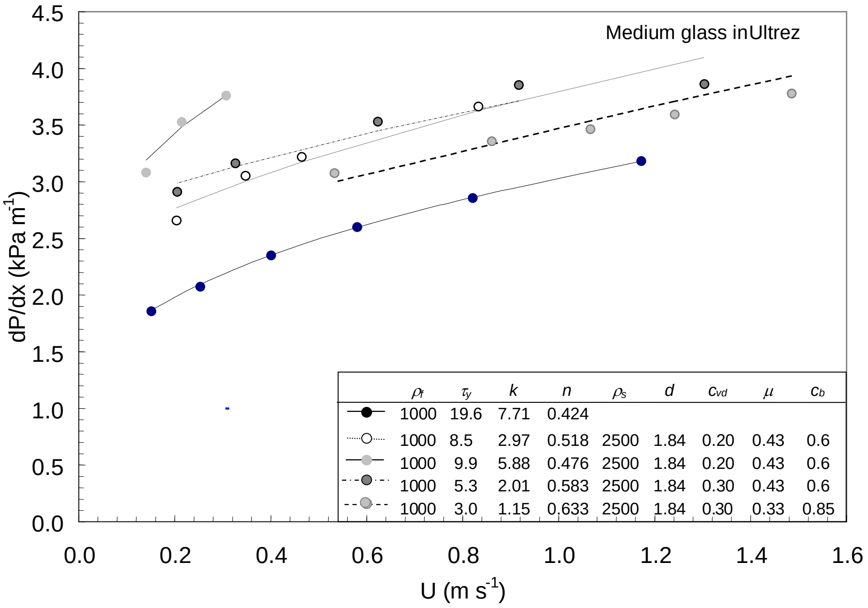


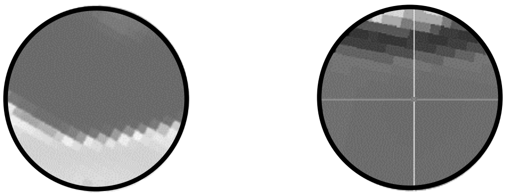
Figure 9 **Stratified model predictions of the transport characteristics of 3 mm crushed glass in Ultrez gels based on carrier fluid rheology and solids properties**

This analysis raises two fundamental questions: (i) how representative are such synthesised suspensions of real pastes, and (ii) if the flow looks so similar to a homogenous fluid, can a pseudo-rheology be ascribed to the paste and used for design?

3.3.1 How representative?

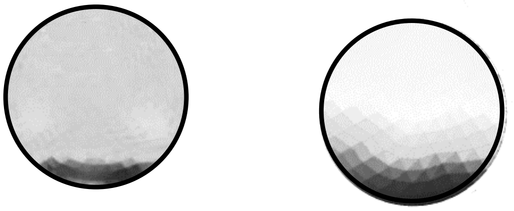
The yield stress of the fluids used in Figure 9 are well below the 100s Pa cited for some pastes, although these higher yield stresses are normally static values obtained from slump or similar tests and are for the entire suspension, rather than for the carrier alone, as used here. Nevertheless the carrier rheology is lower than would normally be used in a paste operation. Furthermore, the “coarse” particles are indeed very coarse, and would only be typical of some form of co-disposal system (e.g. Hourman and Johnson, 2002).

Real suspensions have been tested and concentration profiles across the pipe obtained using electrical resistive tomography (ERT) techniques, some of which are shown below.



3mm sand in
kaolin
250 mm NB

3mm sand in
CMC
100 mm NB



-200μm
25mm NB

-2mm clay
100 mm NB

Figure 10 **ERT concentration maps of four different suspensions. Arbitrary concentration scales**

These ERT tomograms are concentration maps for four different suspensions:

- A 3 mm sand/kaolin co-disposal suspension with similar properties to the synthetic suspension shown above, i.e. τ_y ~ 20Pa, 10% solids concentration, demonstrating that similar behaviour occurs in carrier fluids that are self-aggregating to synthetic polymer based suspensions.
- A 3 mm sand/CMC synthetic co-disposal suspension similar to the synthetic suspension above, demonstrating that solids settling occurs in the absence of a yield stress, but with shear thinning properties.
- A wide continuous size distribution made from thickened oil shale particles at their maximum solids concentration, demonstrating that slurries, which would certainly be considered homogenous, stratify under shear.
- A 200 Pa - 2 mm wide bi-modal size distribution paste demonstrating that industrial pastes stratify under shear.

It is worth noting that these tomograms were all captured within 100-200 diameters of the start of the pipe. To date, all materials tested have shown similar behaviour, implying that the behaviour is ubiquitous, providing the coarse materials are free to settle, i.e. the yield stress, if present, is overcome.

3.3.2 Pseudo rheology?

When Stab-flow was being developed to transport coarse particles a successful design strategy was adopted, whereby empirically obtained multipliers were applied to the underlying carrier fluid’s rheology, to produce a suspension pseudo-rheology. The rational for this was based on the fact that the transport characteristics were very similar to the carrier fluids in form, including apparently turbulent behaviour at similar pipe

Reynolds numbers. Pipelines were designed using this technique (Duckworth et al., 1986) and the approach appeared to work. However, because of the large particles employed, it was necessary to use industrial scale test rigs, so that scale up was rarely more than a factor of 3 and any errors obtained were within a reasonable tolerance. Inherent in this approach is the assumption of homogenous behaviour.

Figure 11 shows typical predictions of transport pressure gradient versus pipe diameter for a constant mass flow of suspension. The actual values will depend upon suspension properties but the form of the results will be the same.

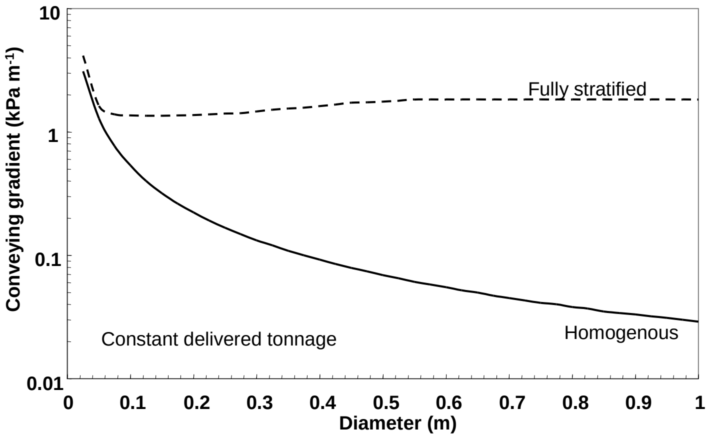


Figure 11 Predicted pressure gradient with pipe diameter for a constant solids mass flow rate using homogenous and stratified models

The pressure gradient is an inverse function of the pipe diameter for laminar flow of a fluid and so the homogenous analysis predicts a pressure gradient which monotonically reduces with increasing pipe diameter. Conversely, the stratified analysis predicts a pressure gradient that is essentially insensitive to pipe diameter for industrial sized pipes, which is in substantial agreement with the pioneering work of Newitt's group (Newitt et al., 1955). Consequently, if the flows stratify, and there is strong evidence that they do, then the pressure gradient based on a pseudo-rheological model obtained from small scale tests, i.e. capillary or rotary viscometers, will grossly under-predict the required transport pressure gradient.

Another feature of this comparison is that for small pipe sizes it is very difficult to distinguish between homogenous and stratified behaviour. Consider the results obtained from tests on the De Beers co-disposal line at Kimberly (Pullum et al., 2004b).

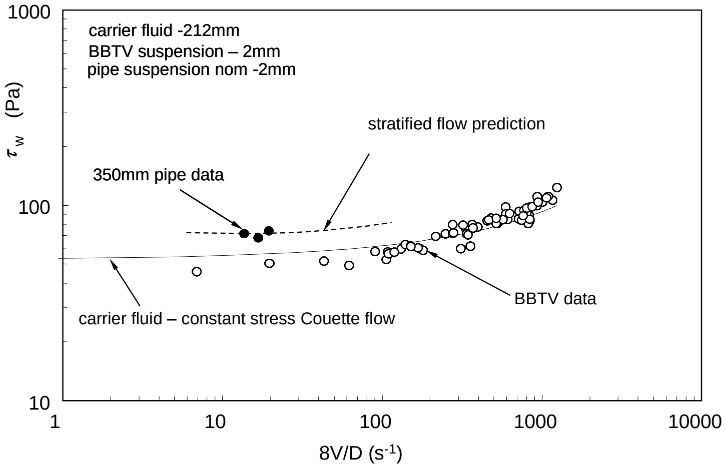


Figure 12 Comparison between capillary tube data and actual pipe data for a stratified co-disposal system

This system adds 2 mm grits to a deep cone thickener underflow which is then pumped to a central discharge deposit. Comparison between the thickener underflow's rheology, measured using a constant stress rotary viscometer, and the total suspensions rheology, using a 12 mm balanced beam tube viscometer (BBTV), is given in Figure 12. The results are essentially the same, implying that the grits will not influence the pressure gradient (or wall shear stress) in the conveying line. Data taken from concurrent full size pipeline tests gave transport gradients, here expressed as wall shear stresses that were substantially higher than this analysis would predict. A stratified analysis, based on the thickener underflow rheology and grit properties, however, accurately predicted this and other actual transport requirements.

Using different instrument geometries can give similarly misleading results. Consider the vane test results shown in Figure 13.

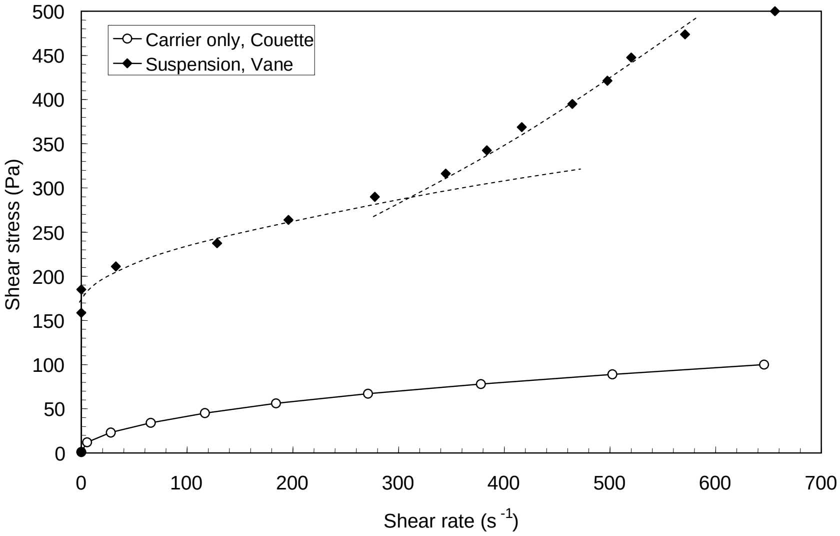


Figure 13 Vane test results for a 55% v/v wide size distribution synthetic paste

In this example, a wide size distribution of solids was added to a polymer gel, representing the carrier fluid, which would normally be composed of ultra-fine particles and water. This carrier fluid's rheology is the lower curve in Figure 13. A vane was inserted into the suspension and the resulting "rheogram" obtained. From this rheogram it appears that the "paste" is a visco-plastic fluid, with a yield stress of order 170 Pa, and, when using this geometry, that secondary flows (often incorrectly described as turbulent) make themselves manifest at shear rates above 280 s^{-1}. Unfortunately, predictions of pipe flow of this suspension, based on these "rheological" values, were incorrect, whereas predictions based on the underlying carrier fluid rheology and coarse particle properties and stratified analysis were in substantial agreement with pipe data.

3.4 Granular Flows – Backfill

Since backfill operations usually require that the material is relatively free draining, the source material is usually made up of solids taken from a filter press, mixed with aggregate and binders of some form. The volumetric concentration is always very high and approaches the maximum packing concentration c_b. The prerequisite that the material is free draining precludes the use of high viscosity carrier fluids, and the flow may be considered to be a packed bed of solids conveyed in a low viscosity fluid, analogous to dense phase pneumatic conveying. Providing the particles sizes are larger than those where inter-particle forces dominate, these flows are relatively insensitive to particle size, but are sensitive to particle size distribution and the solid's shape and density. Because of this insensitivity to particle size, insight into these flows can be obtained by examining the ultra high concentration flows described in §2.

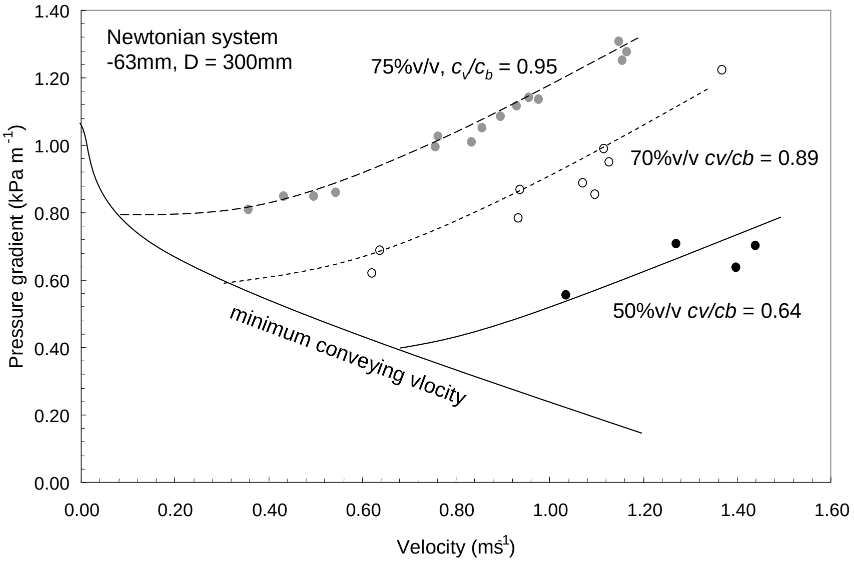


Figure 14 **Transport characteristics of ultra high concentration ROM coal**

Consider the UHC ROM coal transport characteristics shown in Figure 14. This material has a much larger top size than would normally be considered for back fill (-63 mm), but due to the very weak role that actual particle size plays in these flows, it may be considered to be analogous to a backfill suspension. Because of the very high concentrations that these flows operate at, a simple solids' concentration is no longer sufficient to characterize the suspension's behaviour, and the ratio of volume concentration to maximum packing concentration c_v/c_b is used instead. The maximum packing concentration is a strong function of particle size distribution and particle shape distribution, but for rheologically inactive particles, is independent of particle size. The ratio c_v/c_b describes the mobility of the particles; at high values individual particle motion is suppressed, while at low values the particles can reorganize to form bridging arches and dunes etc. Stable operation for these types of material is achieved over the range $0.6 < c_v/c_b < 0.95$. Flow through the plug of particles is a strong function of the underlying carrier fluids rheology and void size, which in turn is a function of c_v/c_b and hence particle shape and size distribution. If the fluid's viscosity is too low, or the plug too porous, high velocities are required to initiate movement, i.e. the minimum conveying velocity is high and blockages can occur. Increasing the width of the particle size distribution improves stability and makes pumping easier (Sundkvist *et al*, 1996). Despite the very high concentrations, the flow is still essentially a stratified flow, as there are no mechanisms to support the particles. A slightly modified version of the Wilson sliding bed model was used to produce the predictions shown as lines in Figure 14 (Pullum et al., 1996). Pressure gradients for these flows are high, but in most backfill operations there is usually more than sufficient static head to deliver the material. As in the previous section, and for the same reasons, pressure gradients for these types of flow are essentially insensitive to pipe diameter.

4 FUTURE DEVELOPMENTS

The increasing environmental and economic pressures on tailings disposal will see high concentration disposal become the norm. Greater understanding of these materials will require more detailed studies of the flow behaviour of the more representative pastes and the development of suitable instrumentation to monitor them. In particular, the development of a rheometer, that can elicit the underlying carrier fluid rheology of a paste, is required if the sorts of models discussed here are to be used on a regular basis for design and control. More sophisticated modelling will also require closer collaboration between fluid dynamicists and soil mechanicists.

Although not the topic of this paper, pumps will need to be improved if they are to efficiently place these materials at the deposit sites. In particular, centrifugal pumps need to be developed, that are less sensitive to high viscosities and high solids loadings, and positive displacement pumps need to be developed to also handle higher and coarser solids content.

5 CONCLUSIONS

A review of various hydraulic transport methods applicable to high concentration suspension like paste and backfill materials has been presented. Detailed investigations have shown that pastes, that would normally be considered stable and homogenous, segregate when subjected to shear. The "fine" particles, where the various inter-particle forces dominate over all other applied forces, form an underlying carrier fluid, while the remainder provide a "coarse" particle burden. These two distinct phases behave in a heterogeneous manner, with the coarse particles typically settling to form beds of sliding material in the pipe. The rheology of the carrier fluid is substantially lower than values obtained by gross rheological measurements of the combined suspension. Attempts to design pipelines and predict the suspension's behaviour based on these gross measurements is unlikely to succeed, especially if considerable scale-up is required. However, mechanistic models that use the underlying carrier fluids rheology and coarse particles properties were shown to accurately predict the suspension's behaviour for a variety of material types and flow regimes.

ACKNOWLEDGEMENTS

Much of the work reported here has been produced as part of the AMIRA P599 project and the support from the sponsors of this project, namely BHP Billiton, CSIRO, De Beers, Rio Tinto and the Weir group is gratefully acknowledged.

REFERENCES

Bhattacharya, A. and Imrie, I. (1986) Development of the asea mineral slurry transport system for coarse coal, Hydraulic transport of solids in pipes. Hydrotransport 10, Innsbruck, Austria, 29-31 October.

Brookes, D.A. and Snoek, P.E. (1986) Stabflow slurry development, Hydrotransport 10, Innsbruck, Austria, 29-31 October.

Brown, N.P. (1988) Three scale-up techniques for stabilized coal-water slurries, Hydrotransport11, Stratford-upon-Avon, England.

Brown, N.P., Streat, M. and Wilson, K.C. (1979) Hydraulic hoisting at high concentration: A new study of friction mechanisms. Hydrotransport 6: Sixth International Conference on the Hydraulic Transport of Solids in Pipes.

Cooke, R. (2002) Laminar flow settling: The potential for unexpected problems, 15th International Conference on Hydrotransport, Banff, Canada.

Duckworth, R.A., Pullum, L. and Lockyear, C. F. (1982) The hydraulic transport of coarse coal at high concentrations, Journal of Pipelines, Vol. 4, pp. 251-265.

Duckworth, R.A., Pullum, L., Lockyear, C.F. and Addie, G.R. (1986) The pipeline transport of coarse materials in a non-Newtonian carrier fluid, 10th International Conference on the Hydraulic Transport of Solids in Pipes, Innsbruck, October.

Hart, B. and Boger, D.V. (2005) Tailings waste minimization, rheology and the triple bottom line. 8th International Seminar on Paste and Thickened Tailings, R. Jewell and S. Barrera (eds), Santiago, Chile, April, pp. 5-27.

Hore, D., McCarthy, D.J. and Pullum, L. (1990) The advantages of a hybrid technology using stabilised flow and ultra high concentration coarse particle transport, Transactions of Mechanical Engineering, 15(3).

Hourman, J. and Johnson, G. (2002) High density disposal of co-thickened kimberlite slurry using positive displacement pumps- a case study, 15th International Conference on Hydrotransport, Banff, Canada.

Jewell, R.J. and Fourie, A.B. (2005) Paste and Thickened Tailings - A Guide, 2nd edition, Australian Centre for Geomechanics.

Lawler, H.L., Cowper, N.T., Pertuit, P. and Tennant, J.D. (1978) Application of stabilised slurry concepts of pipeline transportation of large particle coal. 3rd International Technical Conference on Slurry Transportation, Las Vegas, Nevada.

Newitt, R.D.M., Richardson, J.F., Abbott, M. and Turtle, R.B. (1955) Hydraulic conveying of solids in horizontal pipes, Trans. Inst. Chem Engrs., 33(2), pp. 9-113.

Nguyen, Q.D. and Boger, D.V. (1992) Measuring the flow properties of yield stress fluids, Annual Review of Fluid Mechanics, 24(1), pp. 47-88.

Nguyen, Q.D. and Boger, D.V. (1998) Application of rheology to solving tailings disposal problems, International Journal of Mineral Processing, 54(3-4), pp. 217-233.

Pahias, N. and Boger, D.V. (1996) A fifty cent rheometer for yield stress measurement, Journal of Rheology, 40(6), pp. 1179-1189.

Paterson, A.J.C. (2002) Is slump a valid measure of the rheological properties of high concentration paste slurries? 15th International Conference on Hydrotransport, Banff, Canada.

Pullum, L. and Graham, L.J.W. (2000) The use of magnetic resonance imaging (mri) to probe complex hybrid suspension flows, 10th Transport and Sedimentation Conference, Wroclaw, Poland, September.

Pullum, L., Graham, L.J.W., Rudman, M., Aldham, B. and Hamilton, R. (2006) The ups and downs of paste transport, 9th International Seminar on Paste and Thickened Tailings, R. Jewell, S. Lawson & P. Newman (eds), Limerick, Ireland, 3-7 April, pp. 395-402.

Pullum, L., Graham, L. and Slatter, P. (2004a) A non-Newtonian two layer model and its application to high density hydrotransport, 16th International Conference on Hydrotransport, Santiago.

Pullum, L., McCarthy, D.J. and Longworth, N.J. (1996) Operating experiences with a rotary ram slurry pump to transport ultra-high concentration coarse suspensions, Hydrotransport 13, Johannesburg.

Pullum, L., Slatter, P. and Vietti, A. (2004b) Transport characteristics of a stabilized co-disposal tailing line, 12th Transport and Sedimentation of Solid Particles, Prague, Czech Republic.

Robinsky, E.I. (1975) Thickened discharge – a new approach to tailings disposal, Can. Mining Metal Bull., 68, pp. 47-53.

Rudman, M. and Blackburn, H.M. (2006) Direct numerical simulation of turbulent non-Newtonian flow using a spectral element method, Applied Mathematical Modelling, 30(11), pp. 1229-1248.

Rudman, M., Blackburn, H. M., Graham, L.J.W. and Pullum, L. (2004) Turbulent pipe flow of shear-thinning fluids, Journal of Non-Newtonian Fluid Mechanics, 118(1), pp. 33-48.

Rudman, M., Graham, L.J., Blackburn, H.M. and Pullum, L. (2002) Non-Newtonian turbulent and transitional pipe flow, Hydrotransport 15, Banff, Canada.

Shook, C.A. and Roco, M.C. (1991) Slurry flow. Principles and practice, Butterworth-Heinemann.

Slatter, P.T. and Wasp, E.J. (2000) The laminar/turbulent transition in large pipes, 10th International Conference on Transportation and Sedimentation.

Sofra, F. (2006) Rheological assessment - a road map for plant designers and operators. 9th International Seminar on Paste and Thickened Tailings, R. Jewell, S. Lawson & P. Newman (eds), Limerick, Ireland, 3-7 April, pp. 13-23.

Song, T. and Chiew, Y.M. (1997) Settling characteristics of sediments in moving bingham fluid, Journal of Hydraulic Engineering, 123(9), pp. 812-815.

Sundqvist, Sellgren, A. and Addie, G. (1996) Slurry pipeline friction losses for coarse and high density industrial products, Powder Technology, 89(1-2), pp. 19-28.

Talmon, A.M. and Huisman, M. (2005) Fall velocity of particles in shear flow of drilling fluids, Tunnelling and Underground Space Technology, 20(2), pp. 193-201.

Thomas, A.D. (1978) Pipelining of coarse coal as a stabilized slurry : Another viewpoint, 3rd International Technical Conference on Slurry Transportation, Battelle, US. Slurry Transportation Association.

Thomas, A.D. (1979) Settling of particles in a horizontally sheared Bingham plastic, First National Conference on Rheology, Melbourne.

Thomas, A.D., Pullum, L. and Wilson, K.C. (2004) Stabilised laminar slurry flow: Review, trends and prognosis, 16th International Conference on Hydrotransport, Santiago, Chile.

Wilson, G.W., Miskolczi, J., Dagenais, A.M., Smith, Q., Lanteigne, L., Hulett, L. and Landriault, D. (2006) The application of "Paste rock" for cover system in mine waste management, 9th International Seminar on Paste and Thickened Tailings, R. Jewell, S. Lawson & P. Newman (eds), Limerick, Ireland, 3-7 April, pp. 209-219.

Wilson, K.C. (1976) A unified physically-based analysis of solid-liquid pipeline flow. Hydrotransport 4, Cranfield, England.

Wilson, K.C., Horsley, R.R., Kealy, T., Reizes, J.A. and Horsley, M. (2003) Direct prediction of fall velocities in non-Newtonian materials, International Journal of Mineral Processing, 71(1-4), pp. 17-30.

Wilson, K.C. and Thomas, A.D. (1985) A new analysis of the turbulent flow of non-Newtonian fluids, Canadian Journal of Chem. Eng., 63, pp. 539-546.

NOTATION

c_b	Maximum packing concentration	(-)
c_d	Delivered volumetric concentration	(-)
c_v	Volume concentration	(-)
d	Particle diameter	(m)
SEC	Specific energy consumption	(kWhr (tonne km)$^{-1}$)
V_c	Transitional velocity	(m s-1)
ρ_f	Fluid density	(kg m^{-3})
ρ_m	Mixture density	(kg m^{-3})
ρ_s	Solid density	(kg m^{-3})
τ_y	Yield stress	(Pa)
τ_{yB}	Bingham yield stress	(Pa)
τ_{yc}	Critical yield stress	(Pa)