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Hydraulic Mineral Waste Transport and Storage

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non-Newtonian, slurry, tailings, rheology, hydraulic transport

Abstract

Conventional mineral waste disposal involves pumping dilute concentration suspensions of tailings to large catchment areas, where the solids settle to form a consolidated base while the excess water is evaporated. Unfortunately, this often takes years, if ever, to occur, and the interim period poses a severe threat to the surrounding countryside and water table. A worldwide movement to increase the concentration of these tailings to pastes for disposal above and below ground, obviating some of these issues, has led to the development of new technologies. Increasing the solids concentrations invariably produces non-Newtonian effects that can mask the underlying nature of the suspension mechanics, resulting in the use of poor pipeline and disposal methods. Combining rheological characterization and analysis with non-Newtonian suspension fluid mechanics provides insight into these flows, both laminar and turbulent. These findings provide the necessary basis for successful engineering designs.

1. INTRODUCTION

The production of minerals, metals, and some fuels (e.g., coal and oil sands) via mining and mineral extraction generates enormous volumes of waste. Technological advances in the mining and mineral processing industries have increased the economic viability of refining low-grade ores and, coupled with the continual depletion of high-grade ore deposits, produce continually increasing volumes of this waste, called tailings.

Based on 2010 production figures, it is estimated that the global production of fine-particle waste as tailings exceeds 14 billion metric tons annually (Furstenau 2001, Jones & Boger 2012, Mikula 2012). A single mineral processing plant can produce in one day more than 230,000 metric tons of tailings solids to be pumped to disposal (Boger 2009).

In general, the extraction process consists of mining the ore, comminution or crushing and grinding the ore, followed by hydroprocessing to separate the valuable component from the gangue or waste. The valuable component may be subject to further processing, and the waste or tailings are transferred to a disposal or tailings storage facility (TSF). The material, and the gangue, in particular, is already in the form of an aqueous suspension, and so disposal of this waste material by hydraulic means is an obvious strategy.

It has long been the industry standard to hydrotransport tailings to a prepared disposal or storage site with the aim of allowing the solids to settle and consolidate over time and the water to be removed via decantation and evaporation. However, the settling, consolidation, and water-recovery process can take many years, and conventional tailings disposal, which involves storage in large dams or reservoirs, is problematic for several reasons. Water recovery and land reclamation and rehabilitation cannot be completed in a timely manner, and there is a significant risk of groundwater contamination. Most importantly, as seen in the recent Brazilian Samarco tailings disaster, where 33×10^6 m^3 of tailings destroyed 158 homes and killed 17 people (WISE 2016), dams are prone to failure through leakage, instability, and liquefaction. Since 1961, there have been over 103 major tailings dam failures worldwide, resulting in at least 1,257 human deaths (WISE 2016). Since 2000 alone, there have been over 35 major tailings dam failures, resulting in at least 315 human deaths and the release of over 55×10^6 m^3 of tailings, causing injury, the displacement of people, and environmental damage (WISE 2016). These figures are by no means exhaustive, as many failures are thought to go underreported.

In addition to safety and environmental considerations, there is a distinct worldwide trend toward minimizing water use and storage to reduce operational costs and to increase the profitability of mine operations. In many cases, there is a financial incentive to reduce water consumption and minimize water losses. To protect, manage, and conserve limited water resources, users in an increasing number of countries are required to obtain a license, sometimes on a competitive basis with other users. Alternatively, tariffs may be exacted for water that has been free in the past (e.g., underground sources).

These considerations have led to growing awareness that effective waste management is a prerequisite to a safe and sustainable mining industry. Since the mid-1970s (Robinsky 1975), a major goal in tailings management and disposal has been the reduction of water going to and being stored within the tailings to reduce the tailings volume and water consumption and to improve stability, safety, and ease of rehabilitation. Catastrophic events like the ones described above can be ameliorated, and even prevented, by increasing the tailings solids concentration and viscosity, so that if a dam wall does fail, flows to the surrounding countryside are limited.

Depending upon the amount of water removed from the tailings prior to disposal and the resulting material's rheological characteristics, the dewatered tailings streams are termed thickened

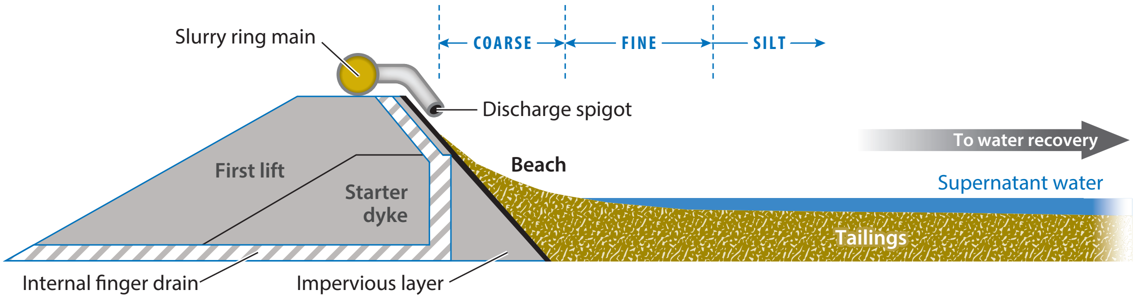

Figure 1

Schematic of a conventional tailings downstream embankment.

tailings or paste tailings (TTPT). TTPTs depend in complex ways on solids concentration, particle size, mineralogy, physical treatment, and the resulting rheological properties.

2. TAILINGS DISPOSAL TECHNOLOGIES

Most tailings are disposed above ground into TSFs; others are disposed underground in a process called backfilling or stope filling, in used open-cut pits, or even in oceans and rivers. The efficacy and indeed possibility of each of these methods depend upon the transport and deposition characteristics of the tailings suspensions, which need to be well understood, quantified, and (where possible) engineered to ensure the preferred disposal technology is optimized.

2.1. Aboveground Disposal

Aboveground disposal was historically achieved using dilute concentration suspensions that readily segregated, consuming large quantities of water. Such modes of disposal are termed conventional in this review. Conventional disposal is still used in many cases where land and water use are not key environmental, financial, or legal considerations. More recently, and with advances in thickener design and operation, higher-concentration disposal methods have been achieved and increasingly implemented. These may be classified in terms of increasing solids concentration as thickened and high-concentration tailings, paste disposal, and dry stacking.

2.1.1. Conventional tailings dams. Most aboveground TSFs can be classified as conventional tailings dams, whereby low-concentration suspensions are discharged into either a naturally occurring depression or a constructed catchment pond or cell. The tailings must be transported in turbulent flow to prevent pipeline blockage due to segregation of the fast-settling particles in the low-viscosity fluid. Once deposited, the suspensions have low viscosity and rely on multispecies sedimentation to produce a graded beach of solids whose diameter decreases with distance from the discharge, as indicated in **Figure 1**.

As the suspension is discharged from the transport piping, settling occurs, with the coarser fractions settling out rapidly to form a steep beach, followed by the slower settling, midsize particles, which produce a less-steep deposit. The finest fractions settle very slowly and may take weeks or even years, if ever, to drop out from the homogeneous supernatant slurry to form an essentially horizontal layer. Thus, the beach of deposited solids is concave, and various models have been produced to predict its profile (Simms et al. 2012). The low concentration of these suspensions (10% $< c <$ 30%) necessitates a large amount of water to transport the solids from the plant, and most of this (>75%) is lost through evaporation, spills, or leakage to the subsurface (Fourie 2012). This loss of water is becoming increasingly expensive, and in many situations (e.g., South Africa, Australia, Chile, Iran, Peru), it simply cannot be tolerated, as the combination of limited rainfall and local demand exceeding renewal makes water a dwindling resource (World Resour. Inst. 2014). Consequently, many countries have imposed permitting restrictions to limit further construction of such dams purely on environmental considerations (see, e.g., Engels 2006).

2.1.2. Thickened and high-concentration tailings. Thickeners using flocculants are used to dewater the tailings to provide a high–solids concentration thickener underflow, which is pumped from the base of the thickener to a TSF, and a relatively clear liquid overflow, which may be recycled to the mineral process. Flocculants are generally large–molecular weight water-soluble polymers used to aggregate fine particles.

Installing a thickener in a tailings circuit and using flocculants to increase the solids concentration of the tailings prior to deposition will not necessarily change the mode of deposition on the TSF. For only moderate thickening, the thickener underflow may be non-Newtonian but still have a low-enough viscosity for flow to the TSF to be turbulent at the desired flow rates. These suspensions behave similarly to conventional tailings, i.e., the coarse (>45-μm) particles are suspended by interaction with the turbulent eddies and form concentration gradients across the pipe. However, because they possess a higher viscosity than water, the settling velocity is reduced, resulting in beach profiles that are flatter and more uniform than those obtained with purely heterogeneous, noninteracting suspensions.

If the thickener underflow has yield stress values in excess of ~50 Pa after passage through the underflow pump(s), laminar flow during transport to the TSF in industrially sized pipes and at typical flow rates and suspension densities is possible, and if the particles are fine (d_{90} less than ~45 μm), segregation and water release will be minimal upon deposition. In these cases, either the particles remain suspended in the fluid to form a homogeneous slurry or the settling velocity of the particles in the viscous carrier fluid is so low that phase separation is very slight. These pseudo-homogeneous slurries can be disposed via a ring main pipeline running around the perimeter of the TSF equipped with discharge spigots spaced along the ring main pipeline to distribute the tailings into the TSF to form a shallow, sloped deposit.

In the 1970s, the Falconbridge Kidd Creek mine in Canada attempted to dispose of thickened tailings using a central thickened discharge system (CTD) (Robinsky 1975, 1978, 1999), and this became the generic model for the disposal of TTPT. A schematic of a variant of this approach is shown in **Figure 2**.

TTPT is pumped under laminar flow to one or a series of rising vertical discharge pipes. Whether the pipes run horizontally, as shown in **Figure 2**, run up ramps, are continually relocated, etc., is a matter of design—the only essential feature is that material be discharged above a rising bed of deposited solids. With many risers, the tailings can be pumped and distributed into various parts of the catchment area, allowing previously filled areas of the catchment to dry and strengthen.

CTD deposits form sloped, conical, or multiply conical, high-concentration deposits, with little if any pondage water, which is normally handled using a small toe dam. Confining dam walls, if employed, are small. The lack of impounded water removes the driving head as a vehicle for the failure and large-scale flooding of conventional tailings dams. The high viscosity of the deposits also inhibits flooding, although care must be exercised in earthquake-prone areas to ensure that liquefaction cannot occur. Furthermore, the ability to discharge material at various locations promotes rapid drying and stiffening of the deposits and earlier rehabilitation.

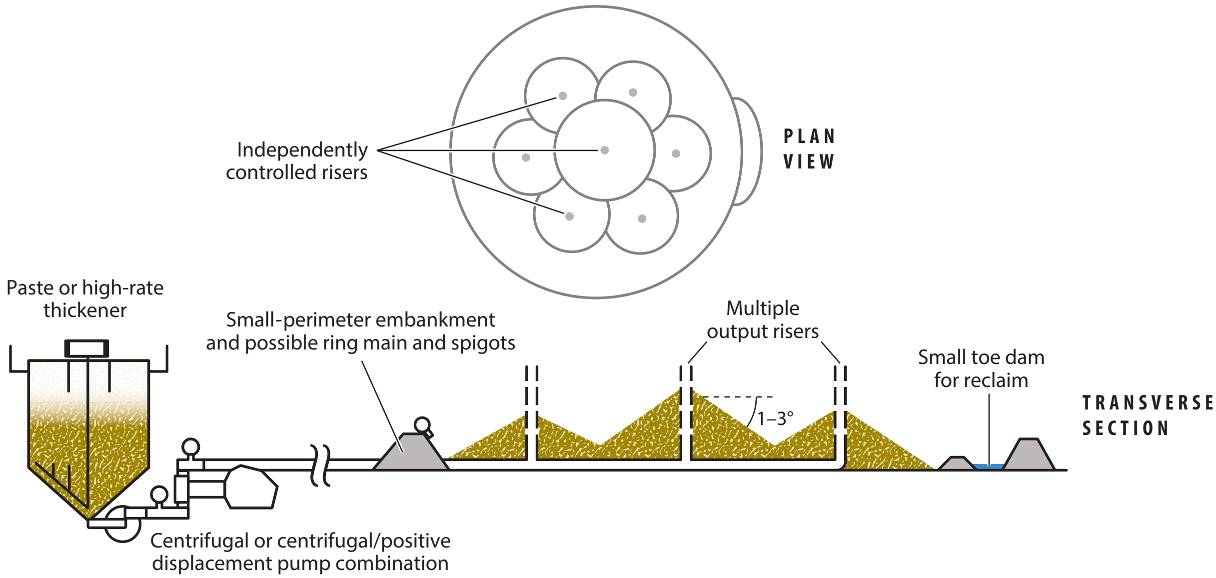

Figure 2

Schematic of a central thickened discharge system, using multiple independent static risers, each equipped with multiple outlets along the riser.

2.1.3. Surface paste disposal. Surface paste disposal is simply an extension of the thickened tailings disposal described in Section 2.1.2. In the case of paste disposal, the tailings display a higher yield stress and viscosity, typically via more extensive thickening, and either CTD or downslope disposal is implemented. The high concentration of the tailings usually results in a denser consolidated base, and can result in a greater slope and thus smaller footprint than that required for conventional tailings disposal.

2.1.4. Dry stacking. Dry stacking involves pumping high-concentration thickened tailings out to a series of specially prepared TSF cells. The tailings are deposited into each cell for a relatively short time period and then the cell is mechanically worked (using bulldozers, for example) to increase the dewatering through a combination of enhanced evaporation and drainage. As this occurs, deposition sequentially moves to adjacent cells, which are then subsequently worked, allowing a progression of deposition, working, and drying/consolidation before the process begins again in the first cell in a cyclical fashion until the desired depth is obtained. This produces a very dry consolidated deposit. However, the cost of this deposit reworking is considerable, and it is only considered viable when there are substantial environmental pressures (Cooling 2006).

2.2. Belowground Disposal

Tailings can be deposited in disused, or end of life, open-cut mine pits before capping as part of a rehabilitation process. Mine tailings are also used to fill stopes in underground mines as both a means of disposal and a means of increasing production. In the latter case, once the stopes are filled with a suitably stable deposit that supports the mine roof, the pillars of ore that previously supported the roof are mined.

2.2.1. Open-cut pits. Filling open-cut pits provides an opportunity to dispose of both the normal tailings and some of the coarse overburden, i.e., coarse rocks generally trucked on site, in a process known as codisposal. Either simultaneously pumping as a stabilized flow (see Section 4.3) or mixing at the disposal point (comingled disposal) can provide very stable deposits, allowing earlier remediation to take place. Alternative scenarios separate the coarse overburden and the tailings, with possible mechanical mixing performed afterwards.

2.2.2. Stope or backfilling. Mine backfill suspensions may be divided into two basic types. First, in hydraulic fill, high-concentration suspensions whose particle size distribution (PSD) is designed to have a relatively high porosity in loose-packed condition are pumped to the stope and allowed to drain to provide a moderately low unconfined compressive strength (UCS) fill. These suspensions are mainly placed underground due to environmental considerations. Second, there is cemented paste backfill, where cement is added to a graded tailings material whose PSD may be modified to produce a high-density, high-UCS material to support the roof and adjacent stopes during further mining.

The mine backfill material is prepared in an aboveground plant and then pumped to a vertical or inclined delivery pipe or borehole that is connected to a series of reticulating pipes at various locations within the mine.

The first such designs allowed the suspension to fall down the vertical (inclined) feeder, so that partially filled pipes, or slack flow, were produced. The driving pressure and hence flow rate through the horizontal lengths could be controlled by varying the length of the unfilled column. However, slack suspension flow is highly erosive, and several failures of piping and ancillary equipment have occurred because of this method (see, e.g., Paterson et al. 1998). A more controlled approach is to use pressure-restricting devices such as ceramic chokes and valves. However, chokes cannot be used with coarse aggregates.

Typically, the pressure gradients needed to drive the flow in the horizontal sections are high. Fortunately, the static head available to drive these flows is usually also very high (often hundreds to thousands of meters of slurry), so this does not pose a problem. A common approach is to employ some form of pseudo-rheology, i.e., to erroneously assume that the backfill paste acts as a homogeneous fluid of the type described in Section 3, to anticipate the transport pressure gradients for these very high-concentration [$c_v > 50\%$ volume for volume (v/v)] granular suspensions, but they are best evaluated using a plug flow analysis, detailed in Section 4.3.1, that accounts for the coarser particle fractions motion.

2.3. In-Line Processing

Currently, there is a strong interest in altering the rheology and dewatering properties of the tailings at or just before deposition onto the TSF. This normally involves the addition of very significant amounts of high–molecular weight flocculant to increase the viscosity of the tailings and to cause rapid and radical dewatering to form a more consolidated deposit.

In either case, it is difficult to successfully introduce active chemicals into generally high-concentration suspensions. Either the suspensions are turbulent, which allows rapid dispersion of the additive though they quickly become laminar, limiting further mixing, or else the suspensions are laminar and non-Newtonian, which presents a notoriously difficult mixing problem. Several strategies are used to address these problems, including simple sparge pipes, exploiting the mixing behavior in plunge pools at the end of the line, and various in-line static mixers (see, e.g., Meijer et al. 2012, Thakur et al. 2003). Because conventional in-line mixers are subject to high erosion and can block the line, new topological mixers that rely purely on folding the flows via geometric or chaotic means are being developed (see, e.g., Carrière 2007, Castelain et al. 2001, Raynal et al. 1997) that use various flow geometries to mix the tailings and additives.

Most flocculated slurries can suffer a reduction in viscosity as a result of aggregate breakage, and the effects of flocculation are destroyed if the shear level is too high or sustained for too long. Introducing the additive at an insufficient distance from the pipe discharge may result in inadequate mixing; too large a distance may result in new structures in the suspensions being destroyed before discharge. Some quantitative measurements of shear stress for mixtures with additives have been made, along with the effect of shear on the additives. These include both laboratory and field measurements (Heath et al. 2006, Owen et al. 2008); such data is invaluable for optimizing this placement.

There are two main effects of the additives. When the issuing tailings suspension is simply thickened by the additives, flow on the TSF is the same as those described in Section 2.1.2. However, when the additives are used to dewater the tailings, a new segregation phenomenon occurs, whereby the highly flocculated solids rapidly settle to a relatively high–yield stress bed, leaving a flowing supernatant fluid that forms channels across the surface of the newly formed bed, which is an extreme form of heterogeneous beaching similar to that described in Section 2.1.1 (see, e.g., Wells et al. 2011).

3. SUSPENSION RHEOLOGY FOR SLURRY HYDROTRANSPORT

For all the tailings disposal technologies outlined above, shifting from disposal of dilute tailings to disposal as TTPT requires additional engineering considerations. This is related to the dewatering and placement operations and, as the subject of this review, the hydraulic transport of tailings throughout the disposal process. These higher-concentration suspensions are invariably non-Newtonian, and rheology and suspension mechanics are essential tools in the overall management of tailings disposal systems and, in particular, of high solids concentration hydrotransport systems.

TTPT has been facilitated by the improved methods for producing and handling high solids concentration slurry/paste systems. Technological advances in thickening, filtration, centrifugation, mixing, and pumping all depend on the increased understanding of the tailings flow behavior and rheology. TTPT suspensions usually exhibit visco-plastic non-Newtonian behaviors, meaning that they possess a yield stress and a viscosity that varies with shear rate.

The yield stress τ_y is the critical shear stress that must be exceeded before irreversible deformation and flow can occur. For applied stresses below the yield stress, the particle network of the suspension deforms elastically, with complete strain recovery after the removal of the stress—i.e., the slurry has solid-like behavior. Above the yield stress, the slurry flows as a fluid. The relationship between the slurry yield stress and the solids concentration is the single most important characteristic for the design and operation of tailings disposal systems. **Figure 3** shows the yield stress as a function of solids concentration for a number of industrially relevant slurries. It is important to note that the yield stress profile is material specific, being a combined function of mineralogy, processing conditions, PSD, surface chemistry, and shear history.

The flow behavior of non-Newtonian mineral slurries is generally represented by a simple relation between the shear stress τ and shear rate $\dot{\gamma}$, which includes a critical shear stress for the onset of flow. Mineral slurries have constitutive relationships that are generally described by the following Bingham and Herschel–Bulkley flow models, shown in Equations 1 and 2, respectively. The viscosity of the slurry (η) can be determined from the local gradient of the flow curve, as shown by Equation 3:

$$\tau(\dot{\gamma}) = \tau_{yB} + \eta_B \dot{\gamma}, \qquad 1.$$

$$\tau(\dot{\gamma}) = \tau_{yHB} + K \dot{\gamma}^n, \qquad 2.$$

$$\eta = \tau / \dot{\gamma}. \qquad 3.$$

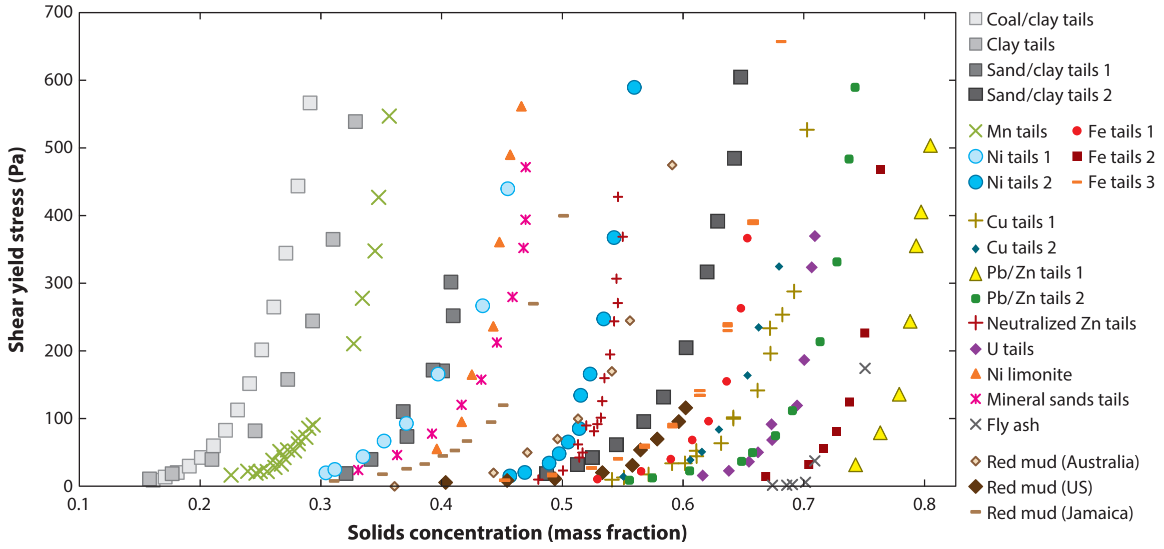

Figure 3

Yield stress for various tailings (tails) samples. Adapted with permission from Boger et al. (2006).

The Bingham model includes a yield stress τ_{yB} with a linear relationship between the shear stress and shear rate with Bingham viscosity η_B. The Hershel–Bulkley model generalizes this to include a power law relationship between the shear stress and the shear rate. A general regime map for tailings transport including unit operations regimes and suitable equipment is shown in **Figure 4** based on material yield stress.

As indicated by Equations 1 and 2, the viscosity of these fluids (i.e., $\eta = \tau/\dot{\gamma}$) rapidly decreases with increasing shear rate; hence they are commonly called shear-thinning or pseudoplastic fluids, where the viscosity is a function of the local shear rate or velocity profile and so will generally vary throughout the flow field. Some tailings exhibit shear-thickening or rheopectic behavior, but these are rarely encountered.

Many suspensions are also sensitive to their shear history and exhibit thixotropic behavior whereby the viscosity reduces with time under shear and its intensity. This reduction in viscosity may be partially or fully recovered upon resting or reducing the applied shear. Where the suspensions have been thickened via dewatering technologies, including thickeners, filters, and centrifuges, the time dependence is often largely irreversible—i.e., the suspensions exhibit rheomalaxis, which is a permanent reduction of the yield stress and viscosity with time of shear resulting from the destruction of the flocculated and/or coagulated structure formed during the thickening process.

The rheology of TTPT suspensions is complex, both chemically and physically, and accurate measurements of the salient parameters are difficult unless one employs specialized techniques. A brief review and description of these techniques and the influence of the major parameters can be found in the **Supplemental Appendix**.

Supplemental Material

Of particular importance is the measurement and definition of the suspension's yield stress. A yield stress defined by extrapolating from a controlled shear/stress rheogram does not necessarily reflect the true yield stress. The dynamic yield stress extrapolated from high–shear rate flow data is

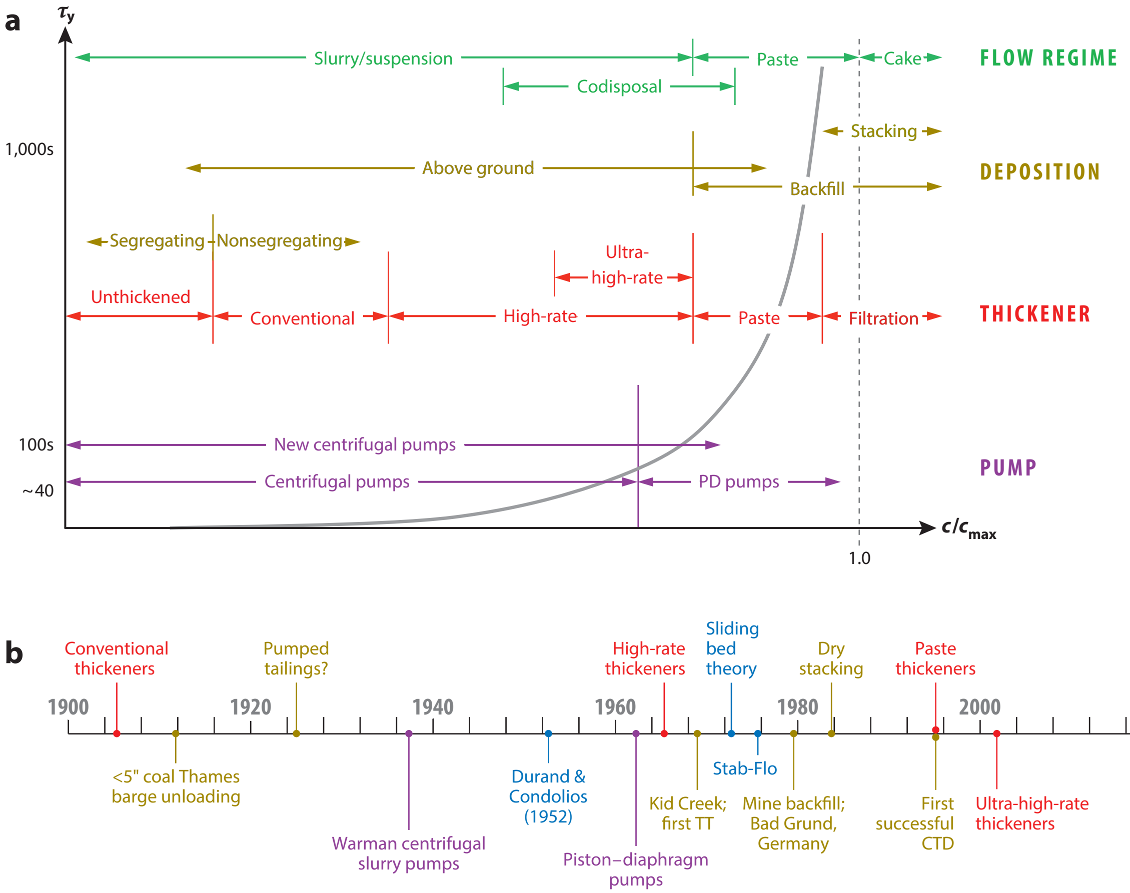

Figure 4

(*a*) Tailings regime and technology map expressed in terms of the variation of the tailings yield stress τ_y with the ratio of solids concentration to the packed solids concentration c/c_{max}. Adapted from Jewell & Fourie (2006). (*b*) An approximate timeline of the development of these and associated technologies. Abbreviations: CTD, central thickened discharge; PD pump, positive displacement pump; TT, thickened tailings.

generally greater than the static yield stress obtained by using a vane technique in an undisturbed sample. The dynamic yield stress plays a significant role in the transport of the tailings to, and the deposition on, the TSF, whereas the true or static yield stress is important in dewatering operations, e.g., determining thickener rate torque requirements, pump selection, pipeline start-up and restart requirements, the development of channels in the TSF, general depositional requirements, and the integrity of the deposit.

4. TRANSPORT

Transporting tailings to the TSF can take various forms, and developments in TTPT technologies provide exciting opportunities for TSF design. However, before these methods can be exploited, the use and limitations of the various transport methods need to be examined to appreciate their limitations and impact on tailings disposal.

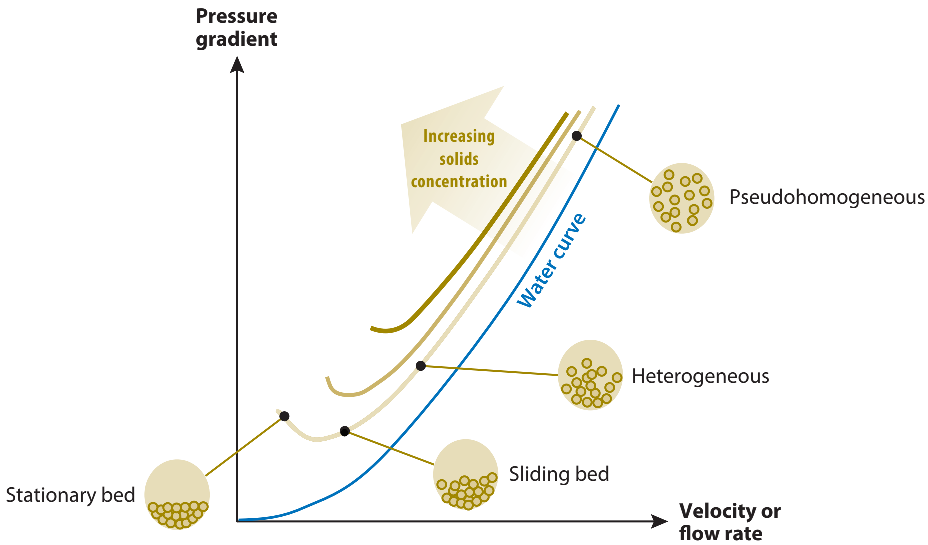

Figure 5

Characteristics of conventional tailings hydraulic transport, showing the influence of increased delivered solids concentration on the pressure gradient.

4.1. Conventional Conveying

Historically, tailings have been disposed into conventional tailings dams (**Figure 1**) as dilute heterogeneous Newtonian suspensions that rapidly settle and form the beaches and impoundment ponds described above. **Figure 5** shows the typical transport characteristics of such dilute suspensions.

The Newtonian fluid, in this case water, is turbulent, which maintains the suspension. For highly turbulent flows (at high velocity), the suspension approaches a pseudohomogeneous mix, whereas at lower intensities, the solids may not be fully suspended, forming the stratified flows shown, and at even lower velocities, the solids may not be transported at all. This results in various limiting velocities, which must be exceeded if the transport of the solids is to be stable, and these limits generally increase with the solids' throughput. A more detailed description of this behavior can be found in the **Supplemental Appendix**.

Supplemental Material

We show below that, in some TTPT suspensions, dependent on mineralogy, solids concentration and particle size and shape have similarities with this form of conveyance.

4.2. Non-Newtonian Homogeneous Suspensions (Slurries)

Many mineral processing plants produce relatively large waste particles ($d > 50$ μm) that are not dominated by strong interparticle forces at low concentrations. However, some processes (e.g., the Bayer process, the production of fine coal, oil sands operations, mineral sands operations, phosphate operations, and the harvesting of fly ash from electrostatic precipitators) produce large amounts of tailings that contain very fine particles, the surfaces of which are electrochemically active. These particles combine with the conveying fluid through colloidal interactions to form non-Newtonian suspensions even at low to moderate concentrations. These suspensions do not readily settle and so cannot be processed in the same way as conventional tailings suspensions. In this review, these mixtures are termed slurries to distinguish them from the more general notion

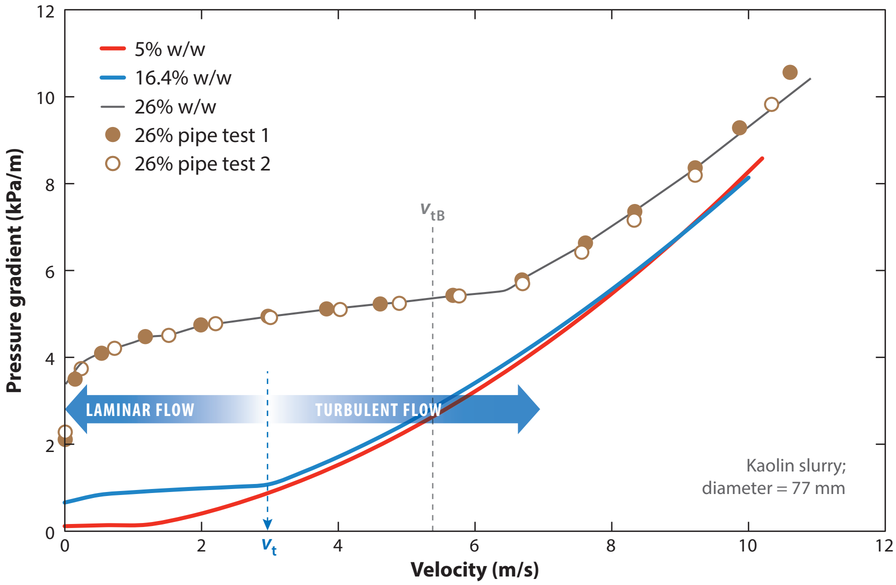

Figure 6

Homogeneous slurry transport characteristics. Solid lines indicate rheological measurement data and circles indicate pipeline test data (Pullum 2015). Abbreviations: v_t, transition velocity; v_{tB}, transition velocity for Bingham plastic fluids; w/w, weight for weight.

of a suspension. **Figure 6** shows the pressure drop transport characteristics of non-Newtonian slurries, typical of concentrated mineral tailings.

The flow is a strong nonlinear function of solids concentration in the laminar flow regime, whereas the inertial turbulent flow is relatively insensitive to this value. It is evident that both laminar and turbulent flows are viable solutions for transporting these slurries, and it is necessary to be able to predict the behavior in both regimes. However, many tailings slurries are too viscous to become turbulent at industrially relevant velocities (see **Figure 7*b***). For laminar flow, analytical solutions relating the wall shear stress to mean velocity can be derived for the rheological model of choice (e.g., see Chhabra & Richardson 1999). Turbulent behavior, as for Newtonian flows, is based on semi-empirical methods (Darby & Melson 1982; Dodge & Metzner 1959; Hanks & Dadia 1971; Slatter 1995, 2000; Stainsby & Chilton 1998). A method by Wilson & Thomas (1985), based on non-Newtonian fluids' greater ability to dissipate turbulent eddies, has almost become the de facto standard for turbulent pipe flow (see **Figure 6**).

The transition velocity v_t denoting the onset of turbulent flow is important because (*a*) it determines which method should be used to predict the flow, and (*b*) it is associated with minimizing the specific energy consumption (SEC). Many workers have proposed relationships for transition (e.g., Darby et al. 1992, Hanks & Ricks 1974, Ryan & Johnson 1959, Slatter 1995), and several (Darby et al. 1992, Slatter & Wasp 2000, Wasp et al. 1977) have found that for Bingham plastic fluids, the transitional velocity v_{tB} is insensitive of pipe diameter and can be approximated by

$$v_{tB} = k_t \sqrt{\frac{\tau_y}{\rho_f}}, \qquad 4.$$

where ρ_f is the slurry density and a range of $22 < k_t < 26$ is typically proposed. **Figure 7*a*** shows that this approximation is essentially true for industrially sized pipes and compares these prediction

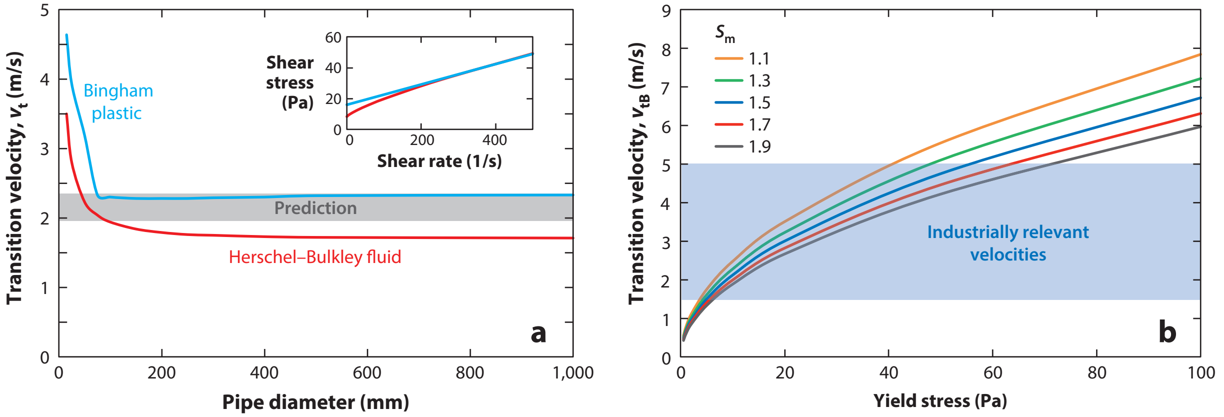

Figure 7

Effect of pipe diameter and rheological properties on transition velocity. (*a*) Prediction of Equation 4 compared with the intersections of laminar and turbulent curves for Bingham plastic and Hershel–Bulkley fluids. The shaded region represents predictions of Equation 4 for $22 < k_t < 26$. (*b*) Transition velocity v_{tB} of Bingham plastic fluids as a function of yield stress and relative suspension density S_m.

ranges with values obtained from the intersection of the extended Buckingham equation for the laminar flow of Bingham and Herschel–Bulkley fluids and turbulent curves produced using Wilson & Thomas's (1985) method.

Because the rheology of these slurries is a strong function of solids concentration, it is essential to examine the variation of the transport pressure gradient or, more particularly, the SEC, which is proportional to both greenhouse gas–equivalent generation and operating costs. Financial considerations usually dictate that minimizing capital costs overrides operating cost considerations. For many high-concentration, fine-particle systems, this means that trains of relatively cheap centrifugal pumps are installed in lieu of the more expensive positive displacement pumps. However, for highly viscous slurries, the efficiencies of centrifugal pumps can be as low as 50% compared to 95% or more for positive displacement pumps. The results are higher energy costs and increases in greenhouse gas emissions, which can exceed the additional cost of a positive displacement pump within a couple years of operation.

Figure 8*a* is typical of the behavior of homogeneous slurries, in this case a large-scale iron ore operation. Consider a slurry that is initially flowing at a relatively low concentration and high velocity. Increasing the solids concentration lowers the overall transport velocity and the concomitant transport pressure gradient required to deliver the same tonnage. However, the slower velocity and higher viscosity, due to the greater loading, also brings the flow closer to laminar flow, switching to laminar flow at some intermediary concentration. As shown in **Figure 6**, the incremental change in the pressure drop in laminar flow is now a weaker function of velocity but a stronger function of solids concentration. In this flow regime, increasing the solids concentration thus further increases the slurry viscosity, increasing the pressure gradient and SEC required, leading to the minima near transition, as shown **Figure 8*a***.

Transitional flow is characterized by intermittent periods of turbulent flow. This periodicity has been observed in the laboratory to provide gentle mixing in the pipe and to resuspend any particles that have settled. This would appear to be a desirable condition for transporting homogeneous slurries, but there are further considerations when transport is provided by centrifugal pumps. Consider the interaction between the system curve (i.e., the relationship between flow and the pressure gradient for a particular pipeline and a given slurry) with a centrifugal pump's

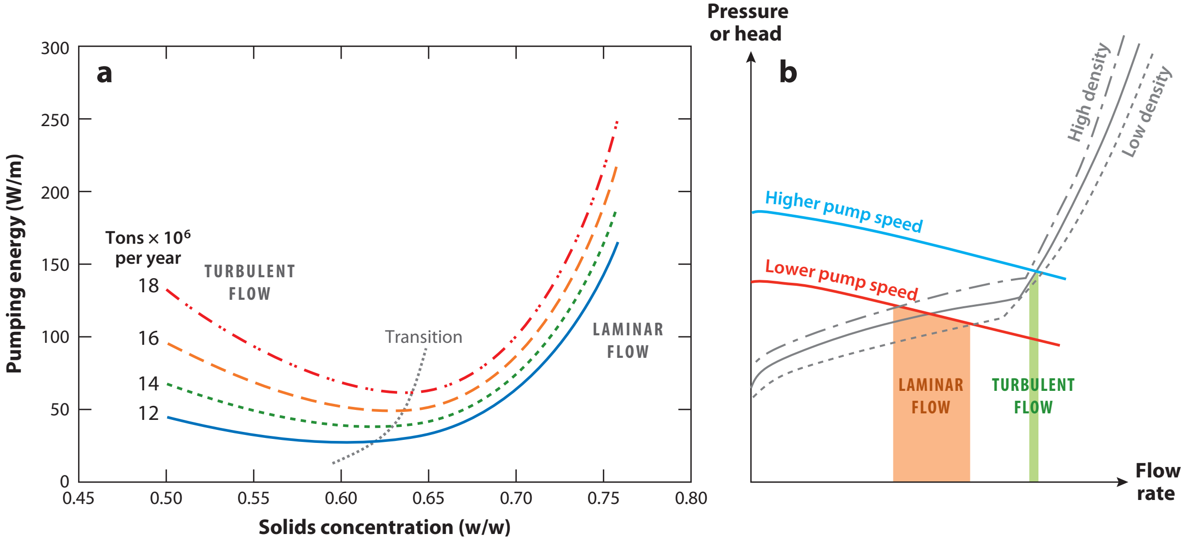

Figure 8

Transitional behavior. (*a*) Variation of pumping energy with solids weight concentration in a commercial iron ore pipeline. The minima correspond to transitional velocities. (*b*) System curve and pump curve interaction for small variations in slurry density, with low density denoted by the dashed line and high density by the dashed-dotted line. In the laminar regime (*orange band*), small variations in slurry density result in relatively large swings in the flow rate, whereas similar changes in the turbulent regime (*green band*) are much smaller. The red and blue lines represent lower and higher speed pump characteristics, respectively. Abbreviation: w/w, weight for weight.

characteristic for the same slurry (i.e., the pressure developed by the pump at a given pump speed and flow rate). The operational point for the pump is where the system curve and the pump's characteristic curve cross (**Figure 8*b***). Small variations in slurry density result in relatively large changes in the flow rate in laminar flow, whereas similar changes in the turbulent regime are much smaller. Greater control is thus achieved by operating just above transition, where the system is less sensitive to minor changes in slurry density.

Laminar pipeline flow is axisymmetric and stable, and many workers have assumed that equivalent stability would be found in channel flows and on layers deposited on the TSF. However, for viscoplastic fluids, surface instabilities develop in the form of streamwise corrugations on the surface of discharging layers (Cochard & Ancey 2009), and large-scale flume tests conducted at Deltares Laboratories in Delft, Netherlands, demonstrated that inhomogeneities form within the channel flow, producing both islands and faster moving channels.

4.3. Non-Newtonian Heterogeneous Suspensions

The ratio of such interparticle forces to the various hydrodynamic and body forces determines whether the particles combine with the fluid to form a slurry. This ratio is a very strong function of particle diameter, and as the diameter increases, the particles rapidly become too massive to be dominated by these interparticle forces, remaining an independent phase with particle path lines differing from the fluid streamlines, i.e., the particle Stokes number St equals $\tau_m U/L > 1$, where τ_m is the particle's momentum relaxation time, $\tau_m = 4\rho_s d/(3C_D \rho_f |\Delta u|)$, Δu is the slip velocity between the phases, and U and L are the characteristic fluid velocity and length scales, respectively. The particle diameter at which this occurs is material specific, but a common upper

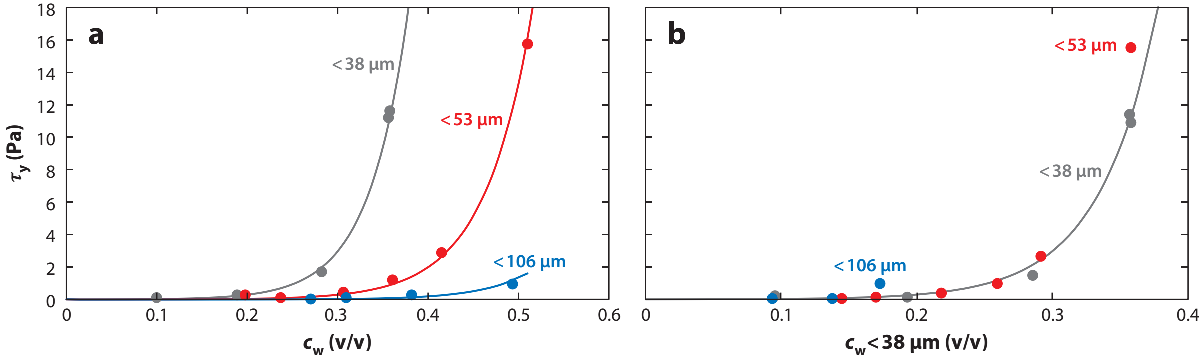

Figure 9

Variation of yield stress τ_y with weight concentration c_w for a thickened uranium tailings suspension: (*a*) total weight concentration and (*b*) weight concentration of particles <38 μm (Coghill et al. 2014).

limit cited in colloidal studies is of the order of 1 μm. This value is too restrictive for mineral materials, as generally the materials are not pure and individual 1-μm particles are rarely found. A more realistic upper limit of 20 μm is often recommended, although a more practical limit of 45 μm, i.e., the smallest common sieve size, is usually adopted. These upper limits are far less than the largest size of many TTPT suspensions, which are erroneously thought to be homogeneous.

Evidence of such an upper limit is given in **Figure 9**, where Coghill et al. (2014) successfully demonstrated that, for several thickened uranium suspensions, particles greater than 38 μm did not contribute to the underlying carrier fluids rheology. The collapse of the various curves onto one implies that, for this system, it is particles smaller than 38 μm that modify the slurry rheology, with the coarser particles behaving as a separate particulate phase or coarse burden.

Figure 10 shows the transport characteristics of two broad PSD suspensions containing a substantial amount of fine clay–like particles and coarse grits. In both panels, the concentrations are defined in terms of a coarse fraction of solids suspended in a finer fraction slurry and thus represent larger overall solids concentrations. The delineation between coarse and fine is in the region of 20–45 μm in each case but is material specific and dependent on the particle morphology and the particle surface chemistry. The bauxite residue fine particle–carrier fluid contained particles less than 45 μm, and the mine waste–carrier fluid contained particles less than 25 μm.

The characteristics appear like those of homogeneous slurries (**Figure 6**) and apparently display both laminar and turbulent flow regimes. Conventional tailings (**Figure 5**) would exhibit unstable operation, e.g., a blocked pipe, at velocities below 3–5 m/s for these suspensions, characterized by a hooked system curve. However, for the flows in **Figure 10**, stable transport is possible at velocities much less than 1 m/s. Both suspensions are viscous, have yield stresses, and do not stratify during storage. Similarly, samples taken from the end of the line are also homogeneous and nonsettling. The width of the PSD is rather extreme, where the ratio of particle diameters d_{85}/d_{50} is greater than 25 and 26 for the bauxite and mine waste, respectively. Many TTPT suspensions with narrower PSDs also exhibit similar behavior, even though most of their particles exceed the upper limit suggested above. Such behavior was also observed for high-concentration, broad coarse coal suspensions examined during the 1970s (Elliot & Gliddon 1970, Lawler et al. 1978, Tellevantos et al. 1979).

Attempts at rheologically characterizing such suspensions as homogeneous slurries are not uncommon, despite the large particle sizes that behave as a separate independent phase and the

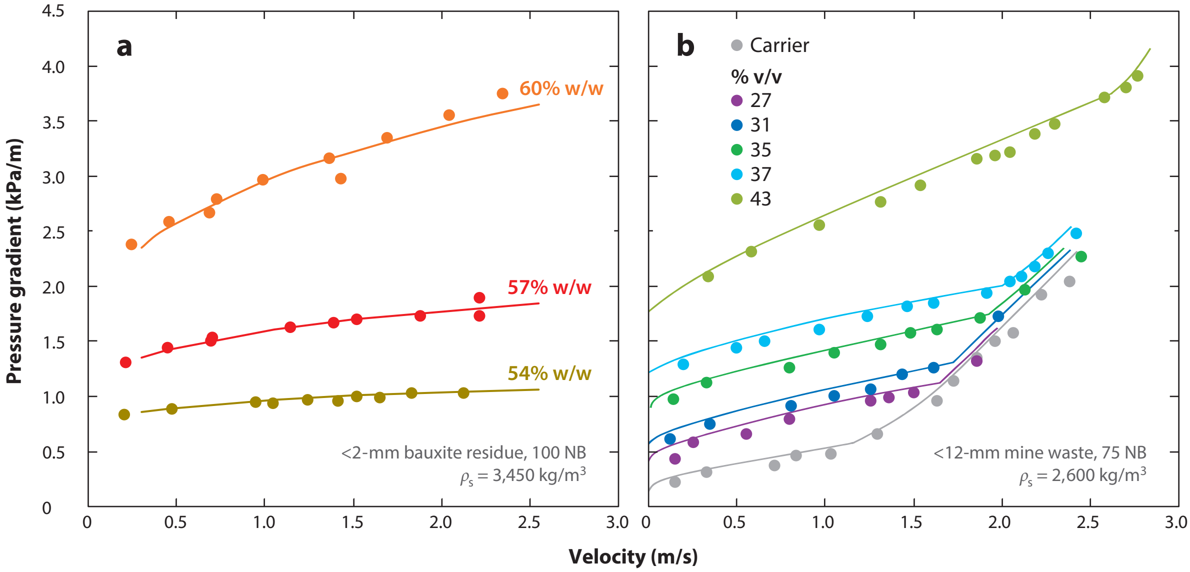

Figure 10

Transport characteristics for broad particle size distribution suspensions: (*a*) bauxite residue suspensions and (*b*) mine waste suspensions conveyed in a clay carrier fluid. Figure adapted from Duckworth et al. (1986a,b). Abbreviations: NB, nominal bore (mm); ρ_s, solids density; v/v, volume for volume; w/w, weight for weight.

expectation or knowledge that settling may occur during testing, i.e., heterogeneous behavior (Cooke 2002).

4.3.1. Laminar flow. The similarity between the conveying characteristics shown in **Figures 6** and **10** resulted in the adoption of pseudorheological models (Brookes & Snoek 1986, Brown 1988, Duckworth et al. 1986b), whereby the apparently homogeneous behavior of the total suspension was estimated based on functions of the underlying carrier rheology and coarse particle concentrations to produce a new homogeneous suspension rheology. Although it was acknowledged that coarser particles could not modify the underlying slurry rheology, there was a belief that if the yield stress of the carrier fluid τ_y were to exceed that required to support the particles under static conditions, i.e., if τ_{yc} were given by Equation 5 below, then coarse solids would be lifted away from the wall of the pipe through the action of shear and rotation at the pipe wall and would then be held in the unsheared core of the pipe. Because the coarse particles would not interact with the pipe wall, they would only increase the conveying gradient by increasing the carrier fluid density and possibly by modifying the extent of a central unsheared core. Uniformly distributed solids across the pipe provided supporting evidence for this type of model (Brookes & Snoek 1986, Duckworth et al. 1983), but in both cases the material involved was low-density lump coal in coal slurries, where the density contrast was very low. Despite the obvious lack of rigor, these methods proved successful in scaling up plant behavior for relatively small incremental steps of pipe diameter, e.g., 150 nominal bore (NB) to 300 NB, and many workers still use such inaccurate arguments to justify their designs (Montserrat et al. 2017).

This approach to modeling these coarse suspension flows was not universally adopted and, e.g., Thomas (1979a,b) suggested that the solids would settle through the action of shear in the pipe. At the same time, stratified models to predict the behavior of heterogeneous flows in Newtonian fluids (Doron et al. 1987, Gillies et al. 1991, Wilson 1976) were beginning to be developed to encompass non-Newtonian fluids, although none of these models contained the spatial variations of the conveying fluids' rheological properties (Clarke & Charles 1993, Lazarus & Cooke 1993).

Using magnetic resonance imaging, Pullum & Graham (1999, 2000) demonstrated that, as Thomas (1979a,b) had predicted, the coarse particles settled across the pipe to form a bed of solids that were dragged along the bottom of the pipe: a sliding bed. Other practitioners observed similar behavior in the field (Cooke 2002).

Using transparent gels as analogs for the underlying carrier slurry, Pullum (2011) was also able to show multiple flow regimes, including one where a separate central core containing solids and a stratified bed coexist. **Supplemental Video 1** shows this and similar behavior.

Supplemental Material

4.3.1.1. Settling in sheared flows. By integrating the fluid's yield stress over the surface of the particle, one can determine a minimum yield stress value τ_{yc} that will prevent the particle from settling:

$$\tau_{yc} = kgd(\rho_s - \rho_f), \quad 5.$$

where $k = 2/(3\pi)$ for spherical particles and $k \approx 0.1$ for typical mineral ore particles with a sphericity of ~0.8 (Thomas 1978, Traynis 1977).

If a particle is placed into a quiescent viscoplastic fluid with a yield stress less than the critical value, $\xi = \tau_y/\tau_{yc} < 1$, an unsheared layer will develop at the upper and lower poles of the particle as it settles, and this enlarged solid will settle at a lower rate. Many formulations have been developed to predict the settling velocity of such an enlarged particle (e.g., Ansley & Smith 1967, Atapattu et al. 1995, Chhabra 1993, Madhav & Chhabra 1995). Where $\xi \geq 1$, the particle will not sink but remains where it is placed. This understanding is of direct use in the settling of solids on the TSF, where the convective velocities are very low, but it is not useful for pipeline flow, where shear is a more important factor and convection times are short (Song & Chiew 1997, Thomas 1979b).

Observations using cylindrical and planar Couette rigs, where the shear rate can be accurately controlled (Highgate & Whorlow 1967, Pullum et al. 2014, Talmon & Huisman 2005, Talmon et al. 2012, Wilson & Horsley 2004), show that when the fluid is sheared, particles that were statically stable sink (see **Supplemental Video 1**). Once sheared, the three-dimensional (3D) network structure that provides the yield stress that supports the particle no longer exists, and the particle is instead surrounded by a viscous fluid, the viscosity of which is now shear-rate dependent.

For settling to occur when $\xi \geq 1$, the fluid must be sheared, but in laminar pipeline flow of a viscoplastic fluid, there is a coaxial unsheared plug of fluid at radii where the applied shear stress is less than the fluid's yield stress and that has a bounding radius $r_p = \zeta R$, where $\zeta = \tau_y/\tau_w$. Thus, settling only occurs in the sheared annular region outside of this plug. Yet observations using various tomographic techniques and transparent gels (**Figure 11**) (Pullum & Graham 1999, 2000) show that the coarse particles sediment across the entire pipe, not just through an annular region. A secondary mechanism must exist to allow the observed fully stratified and partially stratified flows to occur, given that uniformly distributed solids entering the line will be held in this plug.

Solids settling in the sheared annulus migrate to the lower pipe invert, or pipe bottom, where, depending upon the flow conditions, they either form a stationary deposit or form a sliding bed of solids. Because the flow is laminar, they cannot be resuspended through turbulent interactions, although they can form an expanded sheared layer of particles above the bed due to interparticle collisions (Bagnold 1956, Matoušek et al. 2014) and particle suspension due to viscous resuspension (Schaflinger et al. 1990, 1995; Shauly et al. 2000). However, this suspension cannot extend beyond the dynamic center of the flow where the supernatant fluid velocity is at a maximum. The average volumetric concentration of the bed approaches the so-called loose packed condition,

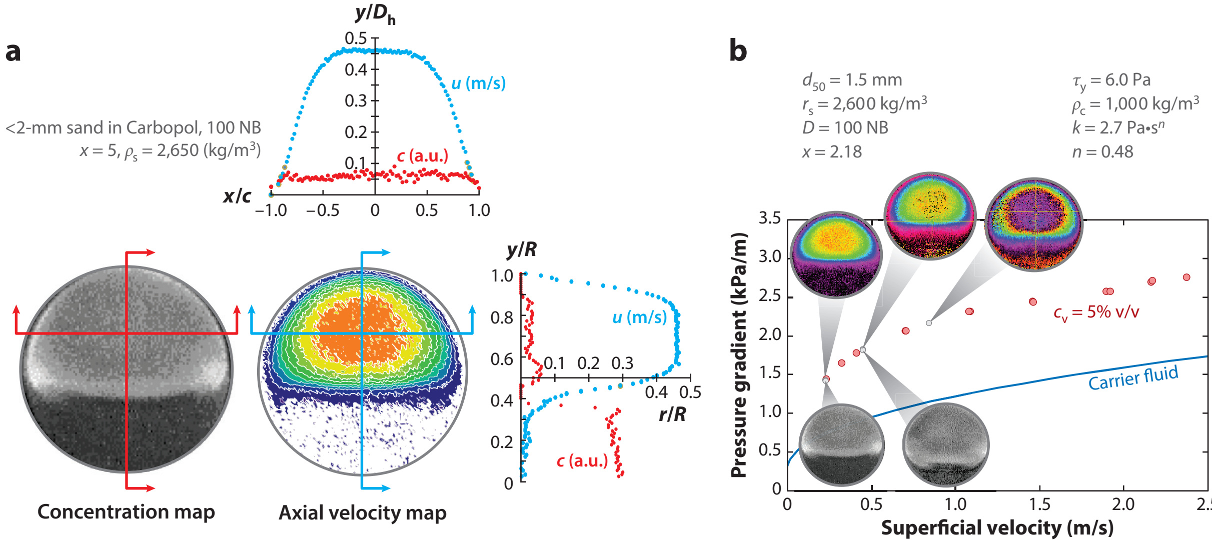

Figure 11

Magnetic resonance imaging concentration and axial velocity maps and profiles for <2-mm sand in Carbopol. (*a*) Concentration at incipient stationary bed formation (arbitrary concentration units). Adapted with permission from Pullum & Graham (1999). (*b*) Bed development during transport, showing concentration (*black and white*) and velocity (*colored*). Adapted with permission from Pullum & Graham (2000). Abbreviations: NB, nominal bore (mm); ρ_f, fluid density; ρ_s, solids density; v/v, volume for volume.

$c_b \approx$ 50–60% v/v, the exact value of which is dependent on the rheology of the carrier fluid and whether a shear layer exists. Talmon & Mastbergen (2004) and Talmon et al. (2014) have observed much lower bed concentrations, $c_b \approx$ 20–45% v/v, calling such beds gelled beds. The dependence of c_b on the applied stresses is a well-observed rheological phenomenon (e.g., Wildemuth & Williams 1984). The settled bed's cross section restricts the fluid flow through the lower invert, changing the flow from axisymmetric to plane-symmetric (**Figure 12**).

The unsheared plug reduces in cross section and moves upwards, exposing particles that were previously contained within the concentric plug to shear and allowing them to settle. Depending upon the depth of the bed and ζ, the newly positioned plug may sweep through the entire original plug back into sheared areas of the pipe, as the dynamic center of the supernatant flow moves upwards with increasing bed depth. This action can thus subject all solids in the original concentric plug to shear such that they settle and form a completely stratified flow (**Figure 11**). If at the flow rate being considered, the plug only partially moves through the original plug of radius r_p, the remnant of the original concentric core will remain filled with solids at the original feed concentration (Pullum 2011, Pullum et al. 2010).

Similar behavior has also been observed in open channels of various cross sections and aspect-ratio flows (e.g., Pirouz et al. 2013, Spelay 2007), which are applicable to transport across the TSF, either in self-formed channels or as sheet flows.

4.3.1.2. Stratified flow models. Stratified flows are amenable to a stratified analysis. Two- and three-layer models have been developed for Newtonian systems (e.g., Doron & Barnea 1993, Eyler et al. 1982, Gillies et al. 1991, Wilson 1976) and differ in detail, such as the number of layers, interfacial behavior, and whether particles are suspended. All models are based on a simple force balance of the type illustrated in **Figure 13**.

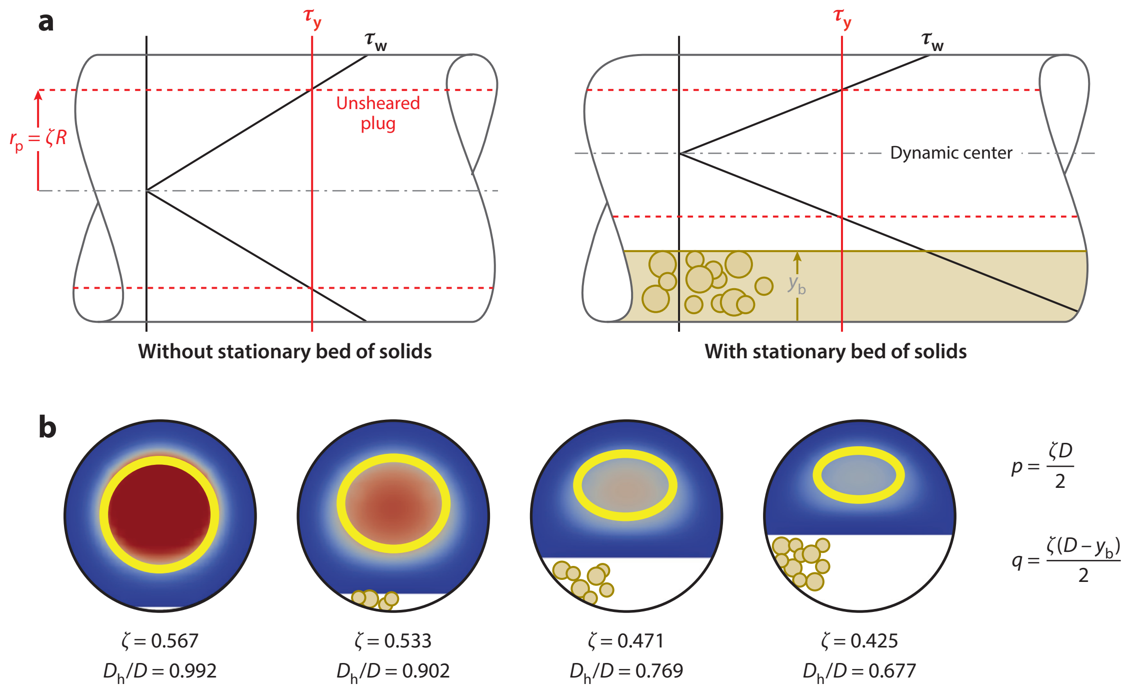

Figure 12

Variation of fluid shear stress with bed depth. (*a*) Schematic drawing showing the fluid's linear stress distribution on the vertical axial plane with (*right*) and without (*left*) a stationary bed of solids. (*b*) Computed stress distributions above the bed for decreasing hydraulic diameter D_h. The yield stress contour, identifying the unsheared plug, is approximated by the yellow ellipses with major axis p and minor axis q. Abbreviations: R, pipe radius; r_p, plug radius; y_b, bed depth; ζ, the ratio of the yield stress τ_y to the wall shear stress τ_w.

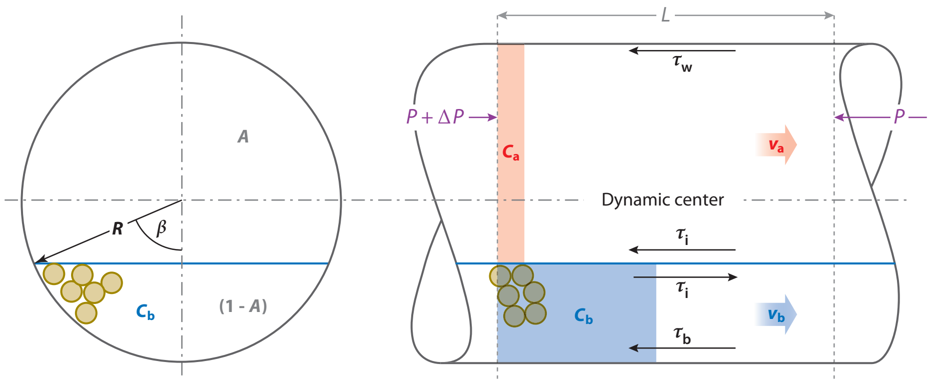

Figure 13

Simple two-layer model, where the solids distribution has been discretized into two regions: above (*red*) and within (*blue*) a bed of solids, with concentration values c_a and c_b and bulk velocities v_a and v_b, respectively. Abbreviations: A, area above the bed; P, static pressure; ΔP, pressure drop across the section; τ_b, under-bed shear stress; τ_i, interface shear stress; τ_w, wall shear stress.

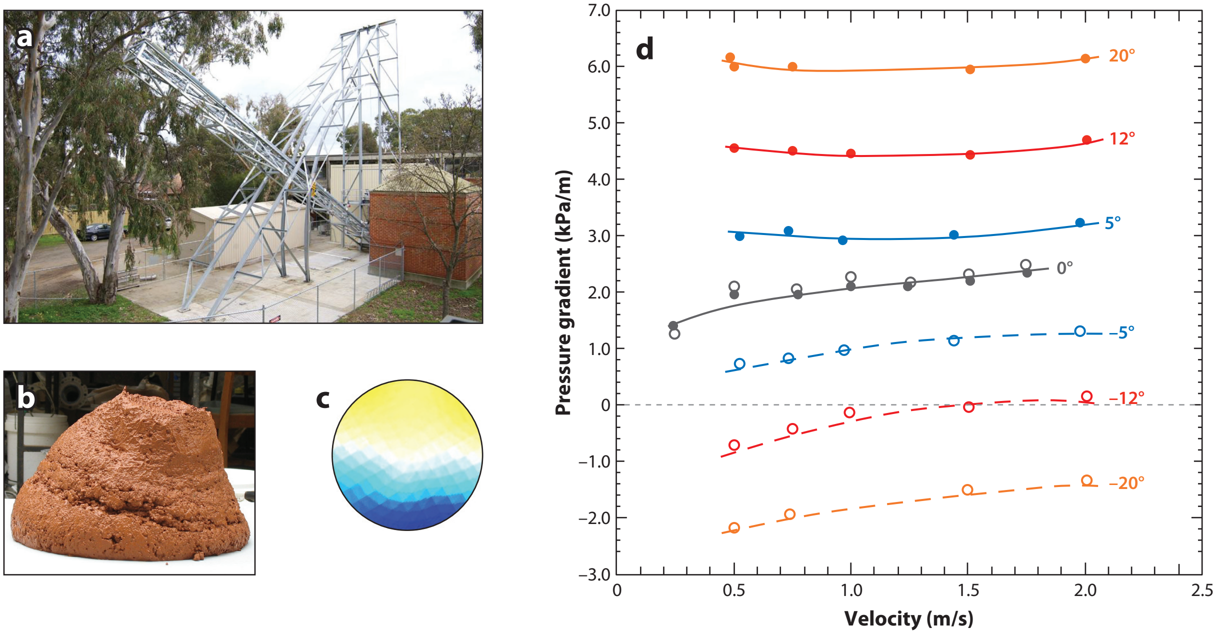

Figure 14

Transport characteristics for backfill suspension: (*a*) inclinable 100 NB pipe loop, (*b*) backfill slump characteristics, (*c*) electrical resistance tomography concentration map 200 pipe diameters downstream from the pump, and (*d*) variation of transport characteristics with ±20° pipe inclination (Pullum et al. 2006). Abbreviation: NB, nominal bore (mm).

In most models, the fluid is Newtonian and the flow regime above the bed is turbulent. These simple models can predict transport characteristics, delivered concentrations, bed depth, and the deposition limit, i.e., the minimum flow rate required to deliver any solids, and have been used successfully for the analysis and design of many conventional hydraulic conveying systems. Although conceptually simple, the various details of these models usually contain a high level of subtle variations, in particular, in the interfacial behaviors and bed formation.

The gross approximations shown in **Figure 13** are almost completely replicated in **Figure 11*a***, where the coarse solids are totally contained in the bed, and the velocities of the bed and the flow above the bed may be considered constant values with reasonable accuracy. Such behavior is an ideal candidate for two-layer modeling, and non-Newtonian stratified flow models have been developed (Pullum et al. 2004, Rojas & Saez 2012) to do this. In these models, the total suspension is split into two parts: (*a*) the carrier fluid, or slurry, comprising the transport media and the fine particles (typically less than 38 μm, as discussed above) and (*b*) the remaining coarser particles, which are the coarse burden to be conveyed. These non-Newtonian models are cognizant of the spatial variation in fluid properties across the pipe and use appropriate rheological models to obtain the various shear stresses, etc., for the models' solutions. Some examples of the capabilities of such a model are shown in **Figures 10** and **14**, which illustrate predictions based solely on the measured underlying carrier fluid rheology, coarse particles concentrations, and other system properties, e.g., the coefficient of sliding friction.

Figure 14*b*,*c* dramatically demonstrates the effect of shear on this very viscous suspension. What appears to be a homogeneous albeit gritty suspension stratifies within 200 pipe diameters

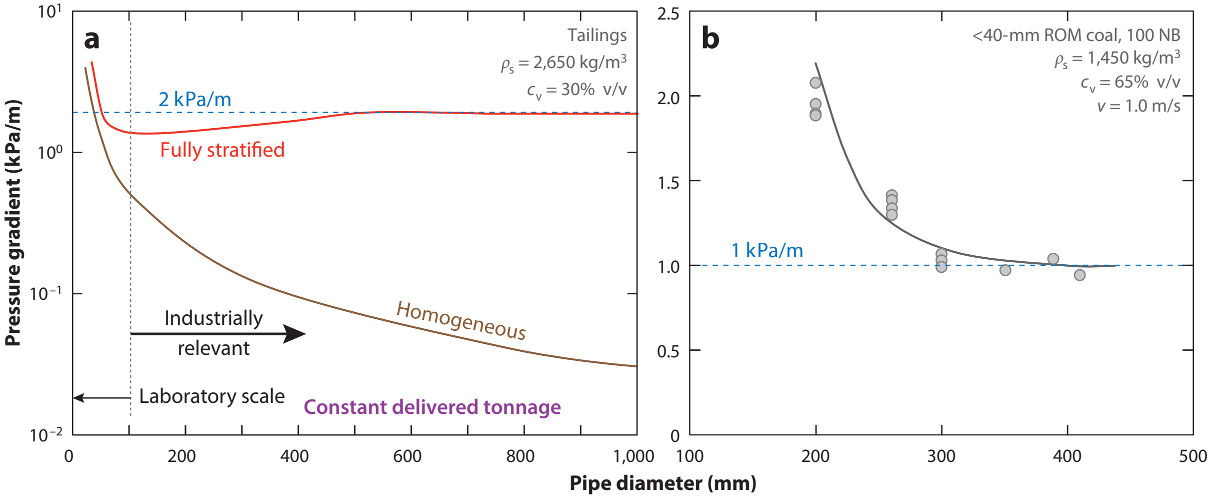

Figure 15

Variation of pressure gradient with pipe diameter: (*a*) homogeneous and fully stratified suspension models and (*b*) ultra-high-concentration, <40-mm run of mine (ROM) coal (Pullum et al. 1996).

(20 m) when conveyed at a relatively low velocity, 1.5 m/s, in laminar flow. Notice also the relatively flat transport characteristics that can even be concave in upward flows (**Figure 14*d***).

Despite grossly appearing to behave like a homogeneous slurry in terms of flow and pressure gradient, the effect of this stratification has profound effects on scale-up. Consider the two cases in **Figure 15*a***. If the suspension is assumed to behave as a homogeneous suspension—not an unreasonable assumption given the gross characteristics—then under laminar flow, the pressure gradient will vary inversely with the pipe diameter to produce the homogeneous curve in **Figure 15*a***. However, if the flow becomes fully stratified, then two-layer models predict that the pressure gradient will become independent of the pipe size to produce the fully stratified curve in **Figure 15*a***, a result previously observed for coarse Newtonian suspensions (Newitt et al. 1955). In small pipes, the viscous forces dominate and the difference between the predictions of the two models is minor. Unfortunately, many laboratory and pilot scale tests are performed using small pipes (e.g., $D < 100$ mm), the extrapolation of which to full-scale would grossly underpredict pressure gradients, as shown. **Figure 15*b*** compares the prediction of a two-layer model with data obtained from large-scale pipelines conveying very high concentrations ($c_v > 70\%$) of run of mine coal, the finer fractions of which combine with the water to form a yield pseudoplastic carrier. Similar behavior was also obtained when pumping broad PSD mine waste. A common rule of thumb in the pipeline industry is that stratified flows will require a transport pressure gradient of 2 kPa/m, which is shown to be a very good approximation of the stratified models' predictions in **Figure 15*a***, but a 100% overprediction for the coal suspension in **Figure 15*b***, even though the volume concentration is approximately double. This difference is primarily due to the change in submerged densities of the particles, but is also due to the mobility of the particles—a function of the grain size, concentration, and flow regime.

4.3.2. Turbulent flow. Modern thickener technologies (e.g., high-rate, high-density, and deep cone thickeners), combined with the effective use of flocculants, can produce thickener underflows with yield stresses between 30 and 200 Pa, or even 400 Pa for some paste thickener/flocculant combinations (Bedell et al. 2015). **Figure 7*b*** suggests that only high-velocity thickened tailings flows could become turbulent. But this is not the case, as the yield stress values quoted for thickener underflows are usually the static yield stresses, not the dynamic yield stresses used in pipeline design. Unless the thickener is built at the immediate discharge to the TSF, the underflow must be transported by pipeline, or occasionally by open flume, to the TSF. For pipelines, either centrifugal pumps or a combination of centrifugal feed pumps and positive displacement pumps is used to transport the underflow. Most thickened suspensions undergo irreversible disruption (rheomalaxis) during passage through the pumps, reducing the viscosity and allowing the flow to become turbulent. Flow into the pumps from the underflow will have high viscosity, and to assist the flow into the centrifugal pump, manufacturers have released various designs with modified impellers, which help induce the pastes into the rotor and/or use enlarged inlets to reduce the suction head.

The relatively high viscosity of the thickened carrier fluids and the relatively small size of the coarse burden mean that particle suspension in turbulent flow is rapid, and almost fully suspended or pseudohomogeneous flow can be attained at moderate-pipe Reynolds numbers. Indeed, many designers assume that once turbulent, the flow can be considered to be homogeneous. However, heterogeneous behavior similar to Newtonian suspensions has been observed for broad non-Newtonian-based suspensions (e.g., Coghill et al. 2014, Shah & Lord 1991), where the system curves rose at low velocity, forming the characteristic hooks, indicative of heterogeneous flow (**Figure 5**). This raises the question of whether methods and correlations developed for Newtonian suspensions can be modified to account for the spatial variation of fluid properties in non-Newtonian flows.

Recent computational studies using direct numerical simulation (DNS) and large-eddy simulation (Gnambode et al. 2015, Rudman et al. 2004, Singh et al. 2014) have examined the low–Reynolds number turbulent flow of viscoplastic fluids typical of that found in turbulent TTPT flows. Because DNS calculates the instantaneous velocity field as a function of time, at any instant in time, the strain rate tensor is calculated from the velocity field at each point in the flow. The contraction of this tensor is used to define a strain rate $\dot{\gamma}$ at each point in the flow that can then be used to define the local, instantaneous viscosity via the rheology model. Clearly, this viscosity varies in space and time as the velocity field varies. As part of the simulation process, the instantaneous viscosity field is also time-averaged to give an average viscosity that is only a function of radius for pipe flow. **Figure 16*b*** shows that the local average turbulent viscosity varies across the pipe, increasing from the wall to the central region of the pipe. This variation affects the settling velocity of the particles across the pipe, because at each location, the particle is immersed in fluid with a different local viscosity, and so particles may settle slowly in the central region of the pipe. This, in turn, changes the solids concentration distribution within the pipe (Pěník et al. 2015).

Many 1D models have been developed to predict the chord-averaged solids concentration across a pipe for Newtonian-based suspensions (e.g., Eskin 2005, 2012; Gillies 1993; Gillies & Shook 1994; Kaushal et al. 2002). Based on the Eskin (2005) model, but using the spatial turbulent variation of viscosity, V. Matoušek & V. Pěník (personal communication) were able to show how viscosplastic fluid rheology could promote particle suspension above that found for equivalent Newtonian flows. In particular, the higher viscosity in the central core reduced the particle settling there, resulting in a more uniformly distributed coarse solids phase, in agreement with chord-averaged electrical resistance tomography data (**Figure 17**). Here, despite the Newtonian and non-Newtonian prediction sharing a common wall viscosity, the non-Newtonian model captures the enhanced solids suspension much better, as shown in **Figure 17**, and corroborates the notion that solids are more readily suspended in non-Newtonian flows. The more

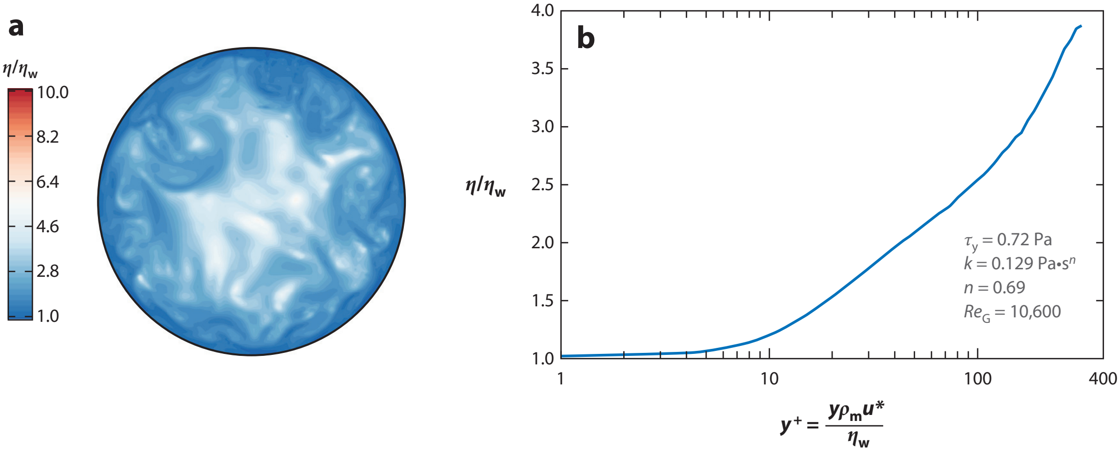

Figure 16

Typical turbulent viscosities in pipeline flow of a viscoplastic fluid flowing at 2.9 m/s through a 50 NB (nominal bore) pipe. (*a*) Snapshot of the normalized instantaneous viscosities across the pipe. (*b*) Variation of the normalized viscosity across the pipe. Adapted from Singh et al. (2016). Abbreviations: η, viscosity; η_w, viscosity at the wall; ρ_m, mixture density; u^*, friction velocity; y, distance from wall.

uniform solids distribution, for the same Reynolds number, implies that sliding beds or hugely stratified flows, the results of poor solids suspension, are unlikely to occur in turbulent TTPT flow.

The success in predicting the settling and suspending behavior of solids in sheared non-Newtonian flows using the local viscosity is encouraging, and it suggests that similar results might be achieved with existing Newtonian heterogeneous hydraulic transport models if similar precautions are taken. Typically, these Newtonian models are semi-empirical, based on data obtained

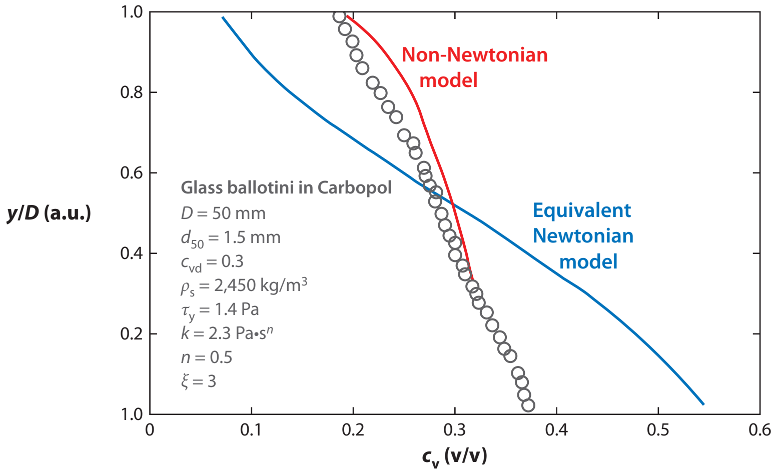

Figure 17

Chord-averaged electrical resistance tomography concentration profile across a pipe, showing the difference in predicted profiles based on a Newtonian fluid and non-Newtonian fluid, each with the same viscosity at the pipe wall. Adapted from V. Matoušek & V. Pěník (personal communication). Abbreviation: c_{vd}, delivered volumetric concentration.

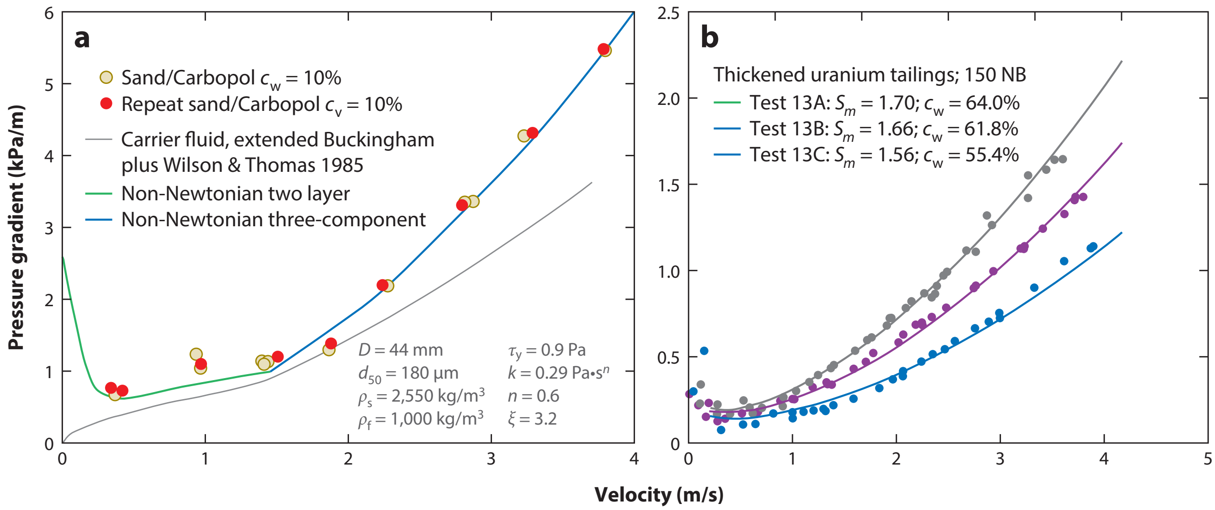

Figure 18

Non-Newtonian suspension predictions. (*a*) Sand in Carbopol showing the underlying carrier fluid (Pullum et al. 2015). (*b*) Thickened uranium tailings modeled with a modified multicomponent model (Coghill et al. 2014). Abbreviation: NB, nominal bore (mm).

with water-based systems (see, e.g., Abulnaga 2002, Shook & Roco 1991, Wilson et al. 2006), and are used to successfully design pipe lines many hundreds of kilometers in length, conveying hundreds of metric tons of solids per hour. As an illustration of this strategy, **Figure 18** shows results obtained using one well-established and multicomponent model that has been validated for a wide range of industrial applications (Clift et al. 1982, Sellgren & Wilson 2007, Wilson et al. 1990) and was modified to account for the non-Newtonian rheology (Coghill et al. 2014, Pullum et al. 2015). In this particular, simple, original model, the solids PSD is split into four fractions, corresponding to very fine particles that increase the fluids viscosity through simple volumetric or Einsteinian effects, a fine particle fraction that is distributed uniformly through the pipeline via turbulent interaction, a larger fraction that forms a heterogenous component, and very coarse particles that are always transported as a sliding bed. In all cases, the coarser fraction is conveyed in a suspension defined by the cumulative effects of the smaller fractions. The non-Newtonian modification combined the first two fractions, which are then described by the rheology of this carrier fluid, e.g., as a Herschel–Bulkley slurry. The third and fourth fractions were identified as before, but now, the variation of the viscosity across the pipe was used to modify the heterogeneous suspensions distribution and stress on the sliding bed. Empirical constants used in the Newtonian version were maintained. Such models are necessarily simple because many of the parameters that might be measurable in laboratories are not available in industrial settings. Clearly, these models will be replaced in the near future by suitable multicomponent computational models, but the authors are unaware of any industrial pipeline that has yet to be designed using such an approach.

Figure 18 demonstrates that, by using this particular modified model, the nature of the turbulent flow of these heterogeneous non-Newtonian suspensions can be successfully captured. Using this method, the accuracy of the predictions of the transport pressure gradients, required for pump sizing, is of order 10–15% (Pullum 2015), comparable to that obtained with the same model used in an extensive study of a wide range of water-based suspensions (Visintainer et al. 2017). Incorporation of the spatial variation of the instantaneous viscosity and the concomitant suspending capabilities of viscoplastic fluids into existing water-based correlations shows promise. This suggests that established, and more importantly, industrially validated, Newtonian fluid methods may be used in these higher-concentration, non-Newtonian flows, giving the confidence necessary to design successful tailings pipelines.

4.4. Homogeneous or Heterogeneous Flow?

The similarity in transport characteristics of homogeneous and heterogeneous flows and their very different scale-up rules are problematic, especially because, outside of the laboratory, measurements of the concentration distributions are unlikely. Guidance is especially needed early in the design phase to assess the likelihood of heterogeneous flow. If most of the particles are of order 50 μm (for typical conditions) or less and the flow regime is expected to be turbulent, then pseudohomogeneous behavior can be expected. If particles exceed 20 μm and the flow regime is laminar, then stratification will occur to form either a sliding or stationary bed dependent on the carrier fluid's yield stress. If samples left in the laboratory for several hours settle or bleed, then stratification under laminar flow is assured, but lack of settling does not ensure that settling will not occur under shear.

For design confidence, it is still necessary to combine viscometric analysis of the carrier fluid with at least one test conducted in a large pipe loop ($D \geq 100$ mm). These loops need to include instrumentation capable of detecting stratification. Accurate scale-up is then readily achieved using the type of mechanistic models described above.

5. CONCLUSIONS

This review has examined the impact that moving to higher concentrations (TTPT) has on both the pipeline transport and deposition of tailings on the TSF. Moving to these higher concentrations substantially reduces the risk associated with conventional tailings dams and the consumption of water, a diminishing resource. The viscosity of TTPT suspensions means that many systems operate under laminar flow, but examination of these flows shows that these suspensions will generally not be homogeneous, and the simple application of rheological models is insufficient to capture the sheared suspensions' behavior, both in the pipe and on the TSF.

The complex interaction between non-Newtonian rheology and particle transport is a relatively unexplored area, and consequently, many avenues of research still need to be pursued before totally robust disposal designs systems can be made. In particular, researchers should examine the effects of concentration and rheology on the hindered settling of particles in sheared viscoplastic fluids to understand how the hindering mechanisms differ from Newtonian behavior. To assist in designing TSFs for TTPT disposal, researchers need a detailed understanding of the flow of turbulent non-Newtonian suspensions in small self-formed channels, those responsible for turbulent transport across the TSF, and its implications on solids transport and hence beach angle. Finally, researchers should develop competent DNSs of yield viscoplastic fluids with coupled discrete element method computer codes to examine the detailed motion of solids in laminar and turbulent yield viscoplastic fluids.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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