Lowered expectations: the impact of yield stress on sand transport in laminar, non-Newtonian slurry flows

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Synopsis

The pipeline transport of paste, backfill or thickened tailings slurries is an important component of the tailings disposal process in many mines around the world. These mixtures contain significant fractions of fine (clay) and coarse (sand) particles, causing them to exhibit non-Newtonian flow behaviour and high frictional pressure gradients. There is often economic incentive to operate these pipelines in the laminar flow regime. Irrefutable evidence has shown that coarse particle settling can occur during the laminar flow of these slurries even when static settling tests show no indication of such behaviour. Previously, a 'rule-of-thumb' minimum frictional pressure gradient of ~1.5 to 2 kPa/m was suggested to ensure effective sand transport, based on the results of tests conducted using viscous Newtonian oils.

In this paper, we examine the results of laminar flow tests of non-Newtonian, coarse-particle laden slurries conducted with pipeline loops of 50, 100, 150 and 250 mm in diameter. The results indicate that the ratio of the mean wall shear stress to the mean surficial particle stress is a better indicator of laminar flow settling tendency than frictional pressure gradient.

Symbols

A	cross-sectional area of pipe, m^2
$C_{0.05}$	chord-averaged coarse particle concentration at $y/D = 0.05$, volume fraction
C_{avg}	averaged *in situ* coarse particle concentration, volume fraction
C_b	*in situ* coarse particle concentration in a settled bed, volume fraction
C_{max}	maximum settled concentration of coarse particles, volume fraction
C_t	total solids concentration, volume fraction
d_{50}	mass median coarse particle diameter, m
D	pipe diameter, m
D'	deposition coefficient as defined by Equation [1]
g	acceleration of gravity (= 9.81), m/s^2
P	pressure, Pa
$-P_z$	frictional pressure gradient, Pa/m
Q	volumetric mixture flow rate, m^3/s
r	radial co-ordinate
v	local (point) velocity, m/s
V	average mixture velocity (= Q/A), m/s
V_t	Particle fall velocity, m/s
y	vertical position measured upward from the bottom of the pipe, m
ΔP	Pitot tube pressure difference, Pa
μ_p	Bingham plastic viscosity, Pa s
ρ	mixture density, kg/m^3
ρ_f	carrier fluid (fines + water) density, kg/m^3
ρ_s	solids density, kg/m^3
τ_p	mean surficial particle stress as defined by Equation [2], Pa
τ_w	mean wall shear stress, Pa
τ_y	Bingham yield stress, Pa

Introduction

Pipeline transport of highly concentrated mineral tailings is now standard practice in the mining industry. Typically, these tailings slurries contain significant fractions of both surface-active fine particles and coarse particles. The principal consequences of handling non-Newtonian slurries of this type are that pipeline friction losses are high and centrifugal pumps may not be appropriate. Additionally, in many cases, it is most economical to operate such pipelines in the laminar flow regime because the mixtures are usually highly concentrated and viscoplastic so that it is not feasible to operate at velocities even approaching the laminar-turbulent transition.

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The body of evidence suggesting that coarse particle settling can occur during the laminar pipeline transport of mixtures of this type is overwhelming. Cooke (2002) and Thomas *et al.* (2004) provide excellent reviews of cases where coarse particle settling was observed in operating pipelines and laboratory pipeline loops. In many of these cases, static settling tests show that the mixture is stable—that is, no coarse particle settling occurs. However, when the same mixture is transported by pipeline, coarse particle settling is observed. Recently, Wilson *et al.* (2003) and Wilson and Horsley (2004) presented a concise and compelling analysis of the fall velocity of particles suspended in non-Newtonian fluids. Their analysis shows unequivocally that the same particle will have a greater fall velocity in a sheared medium than in an unsheared one. There should no longer be any debate about (i) the fact that coarse particle settling can occur in laminar flows and (ii) the absolute irrelevance of static settling tests in determining the tendency of coarse particles to settle during laminar pipeline transport of non-Newtonian mixtures.

The important question that remains is: under what condition(s) can coarse particles remain suspended during the laminar flow of non-Newtonian mixtures? For slurry transport systems that operate under turbulent flow conditions, turbulent eddies provide the mixing force required to suspend the coarse particles (provided they are not too coarse) and prevent accumulation of solids during horizontal pipe flow. During laminar flow, a different mechanism is required to prevent particle settling. A study of laminar flow of a solids-laden Newtonian oil (Gillies *et al.*, 1999) showed that particle transport occurs when the immersed weight of the particles is supported by the interparticle stress, which occurs at frictional pressure gradients of 1.5–2 kPa/m. Numerous researchers (and practitioners) have confirmed that a high pressure gradient is required to effectively transport sand in laminar flows (Thomas, 2000; Cooke, 2002; Wilson and Addie, 2002). The implication is that large pipes cannot be used to transport mixtures of this type, which in turn forces pipeline designers to select high-pressure positive displacement pumps and forsake higher capacity, less expensive centrifugal pumps.

In Canada's oil sand industry, where significant volumes of tailings must be processed, the prospect of using small-diameter pipelines and positive displacement pumps is a strong deterrent to paste technology implementation. Therefore, there is a significant economic prize associated with a critical evaluation of the minimum pressure gradient criterion proposed above. Specifically: does it apply to Newtonian and non-Newtonian fluids? Is it overly conservative for the design of thickened tailings and/or paste transport lines?

This paper describes the results of experiments conducted at the SRC Pipe Flow Technology Centre to begin to evaluate the effects of particle diameter, Bingham carrier fluid properties, pipe diameter and frictional pressure gradient on sand transport. The results of experiments conducted with pipeline loops 50 to 250 mm (nominal) in diameter are presented and a new, tentative correlation based not on pressure gradient, but on Wilson's surficial shear stress, is introduced.

Experimental programme

Pipeline flow experiments were conducted at the Saskatche-wanResearch Council Pipe Flow Technology Centre using idealized mixtures of kaolin clay, coarse sand and water. The water chemistry was controlled to obtain specific viscoplastic carrier fluid (clay + water) properties (Litzenberger and Sumner, 2004). In each case, the carrier fluid was satisfactorily described using the Bingham fluid model. Table I shows the ranges over which the parameters of interest were varied.

The particle size distribution for each of the coarse sands tested here is shown in Figure 1. The distributions shown here were obtained by screening samples of the coarse sand. Subsequent size analyses conducted on samples removed from the different pipe loops showed identical coarse particle size distributions.

The design and layout of the recirculating pipe loops and associated instrumentation used for this study were typical of SRC pipe loops, and are illustrated in Figure 2. Conventional slurry flow measurements, including frictional pressure gradient, volumetric flow rate and averaged *in situ* solids concentration were made for each experimental run. Samples were collected from each loop at regular intervals for off-line analysis of total solids concentration, particle size distribution

Table I

Ranges of parameters tested during the experimental program

Parameter	Range
Pipe inside diameter, D (m)	0.053 to 0.260
Mass median sand particle diameter, d_{50} (mm)	0.1, 0.2, 0.4
Carrier fluid's Bingham plastic viscosity, μ_p (Pa s)	0.014 to 2.6
Carrier fluid's Bingham yield stress, τ_y (Pa)	0 to 130
Total solids volume fraction, C_t (-)	0.2 to 0.6
Coarse solids volume fraction, C_{avg} (-)	0.1 to 0.45
Pipeline average velocity, V (m/s)	0.08 to 3.00
Frictional pressure gradient, $-P_z$ (kPa/m)	0.210 to 17.0

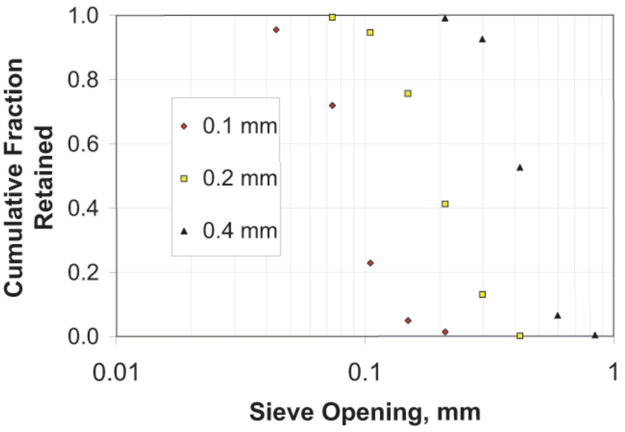

Figure 1—Screen analyses of the coarse (sand) particles used in this investigation

and rheology. Slurry rheology was analysed using both Couette viscometry (carrier fluid only) and vertical tube viscometry (complete slurry). A pipe-over-pipe heat exchanger was used to control the slurry temperature to ± 1°C during each pipe flow experiment.

Two additional types of measurements were made to evaluate the tendency of each slurry to segregate under different operating conditions: a traversing gamma ray gauge and a Pitot tube. On each pipe loop, a traversing gamma ray gauge was located far from the pump discharge. This instrument, which consists of a Cesium 137 gamma ray source and EG&G Ortech detection equipment, was used to determine the chord-averaged solids concentration in the mixture as a function of vertical position in the horizontal pipe. The radiation beam emitted from the source was narrowly collimated to improve the accuracy of the measurements made at each vertical position, y. Measurements were made at 10 equally spaced vertical chords between $y/D = 0.05$ and $y/D = 0.95$. The traversing densitometer was also used to determine the onset of solids deposition along the bottom of the pipe by setting the densitometer at $y/D = 0.05$ and then decreasing the slurry flow rate in stepwise increments. A step-change increase in the solids concentration at this position, $C_{0.05}$, in the pipe indicates that a stationary deposit had formed (Sanders *et al*., 2004).

A Pitot tube was also installed as part of a rotating pipe spool in each loop, in close proximity to the traversing gamma ray gauge (as shown in Figure 2). The Pitot tube provided a measure of the local, time-averaged slurry velocity as a function of radial and vertical position (r, y) by rotating the pipe section and varying the depth of insertion of the probe. It should be noted that we have neglected the Barker correction (Barker, 1922), which is not known for the mixtures of the type tested here, and thus we report the quantity $(2\Delta P/\rho)^{0.5}$, which has units of m/s, rather than the true local velocity, v.

The experimental programme was conducted with the primary objective of evaluating the dependence of laminar flow settling on frictional pressure gradient. In light of this, we introduce a parameter called the deposition coefficient, D':

$$D' = \frac{C_{0.05} - C_{avg}}{C_{\max} - C_{avg}} \qquad [1]$$

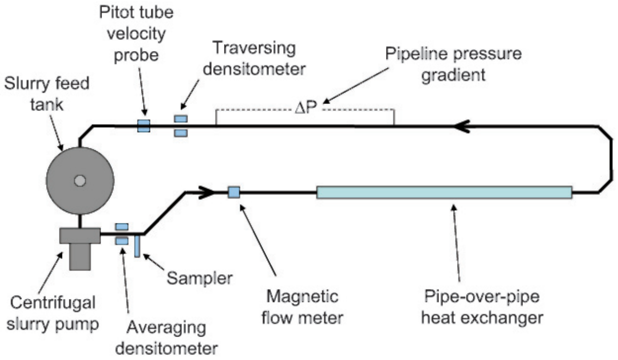

Figure 2—Schematic illustration of the layout and instrumentation of a typical SRC paste flow loop

The deposition coefficient provides an indication of (i) coarse particle segregation in the slurry and (ii) settled bed formation. This parameter is useful because it allows us to compare experiments where the total solids concentrations are different, as runs were conducted at various coarse solids fraction and/or clay concentrations. If D' is low (e.g. ≤ 0), then coarse particle settling is insignificant; if D' approaches 1, one can assume that a stationary (unsheared) deposit has formed at the bottom of the pipe. At intermediate values of D' (e.g. $0.2 \leq D' \leq 0.6$), the sand concentration at $y/D = 0.05$ is greater than the average sand concentration but may not be equal to the settled bed concentration.

We begin by showing some baseline results obtained from experiments conducted using the 100 mm pipe loop, where laminar flow settling is observed at low frictional pressure gradients (Figures 3 and 4) but does not occur when the pressure gradient is high (Figures 5 and 6). The slurry contained 35.4% (by vol.) coarse sand ($d_{50} = 0.2$ mm) and 17.7% (by vol.) kaolin clay, so that $C_t = 0.531$.

The first set of graphs shows results obtained with this slurry after adjusting the water chemistry so that the carrier fluid exhibited a yield stress of 8 Pa. The second set of graphs shows the results obtained with a slurry of identical solids composition but with a carrier fluid Bingham yield stress of 23 Pa. The results obtained with the slurry having the lower carrier fluid yield stress are shown in Figures 3 and 4. Figure 3 shows the variation of both the average wall shear stress, τ_w (where $-P_z = 4\tau_w/D$), and the deposition coefficient, D', with average mixture velocity, V. The results presented in this figure are entirely expected: one observes that the trace of the wall shear stress *v*. pipeline velocity includes both laminar and turbulent flow data, and that the transition from laminar to turbulent flow occurs at about 1.3 m/s. Note also the variation in D' with V: the coarse sand is suspended when the flow is turbulent ($D' \approx -0.2$), while a settled bed forms when the flow is laminar ($D' \approx 0.6$).

The two graphs that comprise Figure 4 show the measurements made with the traversing gamma ray gauge and the Pitot tube at two different pipeline velocities (0.8 and 1.5 m/s). Figure 4a shows the variation in chord-averaged density with vertical position and Figure 4b shows the

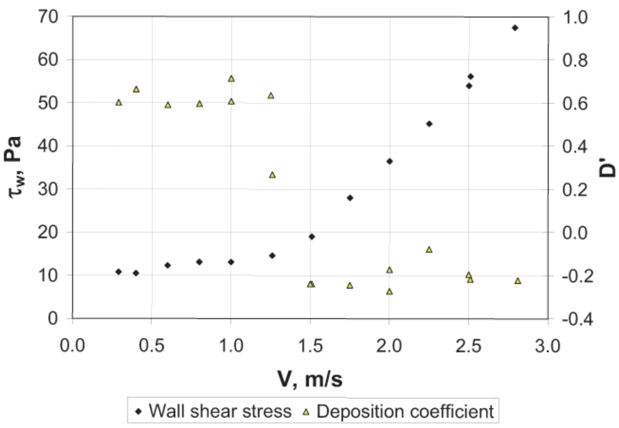

Figure 3—Variation of average wall shear stress (τ_w) and deposition coefficient (D') with average slurry velocity in the SRC 104 mm pipe loop; coarse particle $d_{50} = 0.2$ mm; $C_{avg} = 0.354$; $C_t = 0.531$; τ_y (carrier fluid) = 8 Pa

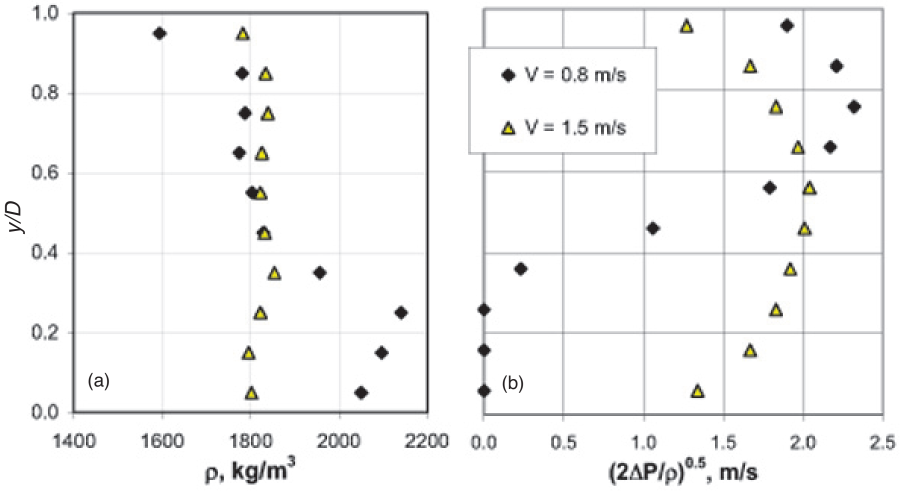

Figure 4—Concentration and velocity distributions for the slurry described in Figure 3: (a) chord-averaged slurry density; (b) approximate local velocity measured along the vertical axis

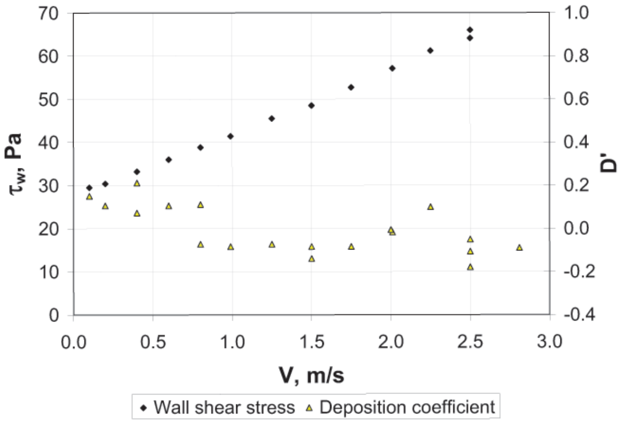

Figure 5—Variation of average wall shear stress (τ_w) and deposition coefficient (D′) with average slurry velocity in the SRC 104 mm pipe loop; coarse particle d_{50} = 0.2 mm; C_{avg} = 0.354; C_t = 0.531; τ_y (carrier fluid) = 23 Pa

approximate local velocity measured along the vertical axis of the pipe. Note that the lower velocity falls within the laminar flow regime while the greater velocity provides turbulent flow conditions for this slurry. Both sets of measurements are consistent with the measurements and analysis of Figure 3, where a high-concentration, essentially stationary bed is found when V = 0.8 m/s.

We now consider the results obtained with a slurry having an essentially identical solids composition but a significantly greater carrier fluid Bingham yield stress (τ_W = 23 Pa). Figure 5 shows that the flow is laminar at each velocity and that that the deposition coefficient is low. It seems likely that laminar flow settling would be observed at the lowest pipeline velocities, where $D' \approx 0.2$ and $-P_Z \approx$ 1.2 kPa/m, if a slurry were transported under these conditions in a longer, once-through pipeline. Similarly, Figures 6a and 6b show no indications of coarse particle settling at V = 0.8 or 1.5 m/s.

Figure 7 shows the deposition coefficient, D', plotted as a function of frictional pressure gradient, $-P_Z$, for all of the experiments conducted with d_{50} = 0.2 mm. Results obtained with 53, 104 and 154 mm pipe loops are shown. The results presented in this figure succinctly frame the problem at hand. Ideally, all the data points for which $-P_Z < 2$ kPa/m would result in $D' > 0$, if the pressure gradient criterion developed for Newtonian flows were also applicable here. It is evident from the results shown in Figure 7 that this is not the case: there are many points for which $D' \leq 0$ when $-P_Z < 2$ kPa/m, just as there are a number of points where $D' > 0$ when $-P_Z >$ 2 kPa/m. If one considers the data collected for each pipe diameter separately, the inadequacy of the pressure gradient criterion is clearly established: for the 53 mm pipe tests, the minimum acceptable pressure gradient required to obtain deposition coefficient values that are consistently low ($D' \leq 0$) appears to be $-P_Z \geq 3.5$ kPa/m. For the 104 mm pipe tests, one might suggest that $-P_Z \geq 1.3$ kPa/m to ensure that D' is low. Finally, for the limited number of 154 mm pipe tests (5 data points), it appears that the minimum pressure gradient is 2 kPa/m.

An alternative non-Newtonian, laminar flow settling criterion is required.

Development of a new laminar flow settling criterion

Before describing the development of a new laminar flow settling criterion, it is instructive to review the objective and key findings of the study conducted by Gillies *et al.* (1999), which provided the basis for the minimum pressure gradient criterion mentioned previously. The focus of their research was to develop a physically meaningful relationship between the *in situ* and delivered concentrations for coarse particles being transported in laminar, Newtonian flows such as those found during production from horizontally drilled heavy oil wells. In this paper, Gillies and co-workers describe a model for the variation of coarse particle concentration with vertical position ($-\partial C/\partial y$) by assuming that the (downward) force of the immersed weight of the particles is balanced by interparticle repulsion forces. The interparticle repulsion forces were modelled by considering the higher-order terms in the expression that relates slurry viscosity to coarse particle concentration (Shook *et al.*, 2002). Their model

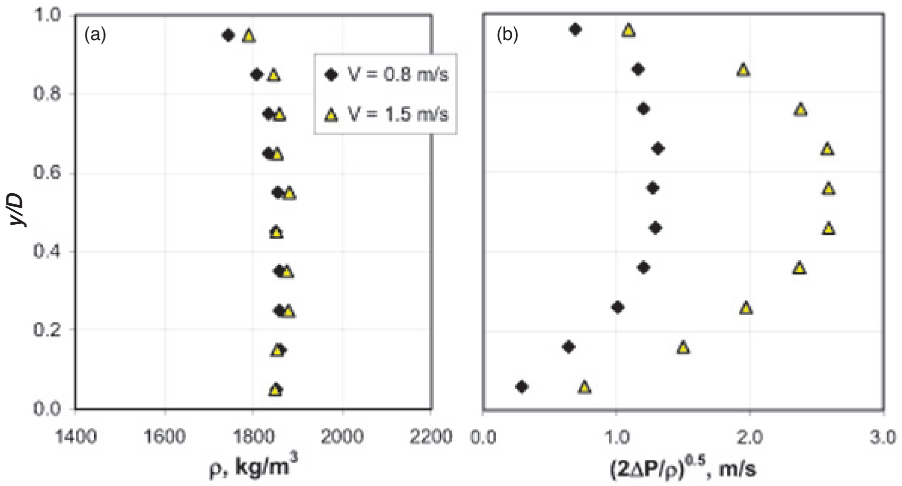

Figure 6—Concentration and velocity distributions for the slurry described in Figure 5: (a) chord-averaged slurry density; (b) approximate local velocity measured along the vertical axis

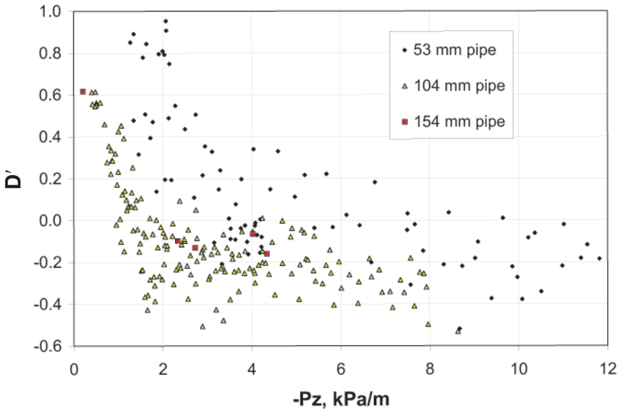

Figure 7—Variation of deposition coefficient (D') with frictional pressure gradient ($-P_z$) for laminar flow experiments; coarse particle d_{50} = 0.2 mm

provides satisfactory predictions of both concentration and velocity distributions of coarse particles during laminar, Newtonian flow. Interestingly, their model shows no relationship between particle size and sand transport effectiveness.

Clearly, the direct application of the above-mentioned model to non-Newtonian laminar flows should be the cause of some concern unless it is plausible to ignore a slurry's yield stress and use the plastic viscosity as a direct analogue of the Newtonian viscosity. Another concern that arises is that the model was developed primarily to model concentration distributions, not particle deposition. Gillies and co-workers also note that a pressure gradient lower than 2 kPa/m would be required for effective sand transport as the difference between the particle and fluid density decreases. Finally, Gillies *et al.* point out that during their study, 'at intermediate pressure gradients, the computed concentration profile depends on whether the bed is initially assumed to be dilated or not'. In other words, if the settled bed concentration is near the maximum packing fraction for a given slurry, particles cannot slide past each other; but if the settled bed concentration is 'low' (relative to the maximum packing fraction), then sand transport at lower pressure gradients is likely. This observation appears to be relevant to the present study, partly because of the type of slurries studied here, where the settled bed fraction for coarse particles in a highly non-Newtonian carrieer depends upon carrier fluid properties and operating conditions.

Recognizing the complexity associated with the application of the Newtonian laminar flow settling model to non-Newtonian slurries, we turn our attention to the recent publications of Wilson and co-workers that were described in the introduction of this paper. Wilson and co-workers define an average surficial particle shear stress, τ_p as:

$$\tau_p = \frac{(\rho_s - \rho_f) g d_p}{6} \qquad [2]$$

Wilson *et al.* (2003) and Wilson and Horsley (2004) have demonstrated the importance of this parameter in determining fall velocities of particles through non-Newtonian fluids. Thus, in our first approximation of the forces acting on a coarse particle being transported in the horizontal pipe flow of a non-Newtonian fluid, we assume that the mean surficial shear stress provides an indication of the tendency of a particle to settle. We then assume that the impelling force is proportional to the average wall shear stress, τ_W. Finally, we check to see if the ratio τ_W/τ_p provides an improved laminar flow settling criterion.

Figure 8 again shows the data of Figure 7, but replotted with the ratio τ_W/τ_p as the abscissa. While there is still considerable scatter in the data, use of the new correlating parameter appears to help collapse the 53 mm and 104 mm pipe data and reduces some of the scatter in the area of greatest importance, i.e. where the deposition coefficient is greater than zero.

Figure 9 shows the data collected for each of the three different pipe sizes and all of the different slurries tested (see Table I). The bulk of the new data points (primarily for slurries with a coarse particle d_{50} of 0.4 mm in the 154 mm pipe loop and slurries with a coarse particle d_{50} of 0.1 mm in the 256 mm pipe loop) have shear stress ratios between 12

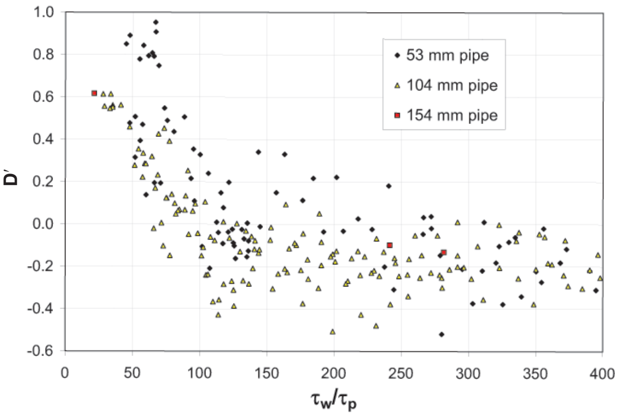

Figure 8—Variation of deposition coefficient (*D′*) with the shear stress ratio (τ_w/τ_p) for laminar flow experiments; coarse particle d_{50} = 0.2 mm

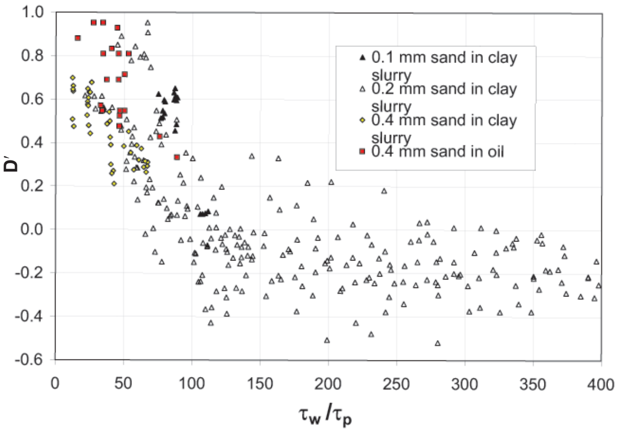

Figure 9—Variation of deposition coefficient (*D′*) with the shear stress ratio (τ_w/τ_p) for non-Newtonian laminar flow experiments with different coarse particle diameters. The sand in Newtonian oil data of Gillies *et al.* (1999) are also shown

and 112, but the degree of scatter in this range is not greatly exaggerated when the additional data points are added. It is evident that slurries with shear stress ratios less than 60 consistently present laminar flow settling. Based on these data, a conservative design would be one in which the shear stress ratio were 100 or greater.

It appears that the ratio of the average wall shear stress to the mean surficial particle stress provides a somewhat improved non-Newtonian laminar flow settling criterion (compared to the pressure gradient criterion). However, this is offered only as a tentative criterion. There is a degree of scatter in the data, even for a single pipe size and particularly for shear stress ratios between 60 and 100, that is not entirely palatable. Possible causes for the scatter include: (i) tests were conducted using recirculating pipeloops and (ii) the variation of the settled bed concentration, C_b, with carrier fluid properties and above-bed flow conditions is not known.

With respect to point (i) we offer an illustrative calculation of the fall velocity, V_t, of a 0.4 mm particle through a non-Newtonian carrier fluid in a 104 mm pipeline. We consider a case for which V = 1.0 m/s; τ_w = 4.14 Pa; ρ_f = 1450 kg/m^3; τ_y = 23 Pa and μ_p = 0.05 Pa s. Using the procedure outlined by Wilson and Horsley (2004), V_t = 0.35 mm/s so that the particle would travel *ca.* 150 m in the time required for it to settle from the centre of the pipe (r = 0) to the pipe invert (r = D/2). This is clearly an oversimplified analysis but does suggest that rather long pipe loops are required if the coarse particle size is relatively small or the carrier fluid is highly viscoplastic.

With respect to point (ii), we have no reliable method for the *in situ* determination of the true settled bed concentration, C_b, for slurries of the type tested here. We note that for the tests involving 0.4 mm sand particles, we expect C_{max} ~ 0.62; however, our experimental results showed that $C_{0.05}$ ≤ 0.5. Therefore, we conclude that by our standard definition, none of our experiments showed a true settled bed despite the fact that the velocity in the lower portion of the pipe was essentially zero. Evidently, the difference between $C_{\max}$ and the observed C_b for the *in situ* settled bed could be an important cause of the scatter in the D' vs. shear stress ratio data.

We are presently analysing the results of a subsequent study to determine the applicability of the shear stress criterion to solids-laden, non-Newtonian flow in a 500 mm pipe loop. Additionally, we are working to more rigorously relate the physics on non-Newtonian, laminar flow settling to the new shear stress ratio criterion.

Conclusions and recommendations

Experiments conducted with mixtures of a non-Newtonian carrier fluid of kaolin clay and water and coarse particles of different diameters show that the 2 kPa/m 'rule of thumb' to ensure that laminar flow settling does not occur may not be the most appropriate criterion to apply. Instead, we offer a tentative criterion based on the ratio of the mean wall shear stress to the mean surficial particle stress. The data show that a slurry's proclivity to experience laminar flow settling is greatly reduced when τ_w/τ_p > 60 and nearly eliminated when τ_w/τ_p > 100. This criterion is in reasonable agreement with the results of flow tests conducted with pipe loops of 50, 100, 150 and 250 mm in diameter.

There is still considerable scatter in the plot of the deposition coefficient as a function of the shear stress ratio. The fact that the experiments have been conducted with recirculating pipe loops may play a role in the scatter observed in the data. Additionally, low values of C_b in the stationary bed, which has been shown to occur, could enhance sand transport effectiveness at lower values of τ_w/τ_p. The low coarse particle concentration in the stationary bed (compared to the settled bed concentration, $C_{\max}$) is related to the viscoplastic properties of the carrier fluid.

Additional experiments in longer pipelines and additional, more rigorous modelling efforts are presently underway. Ideally, an experimental programme involving a once-through system would be conducted under highly controlled conditions to evaluate the application of the shear stress criterion to a more industrially analogous system.

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