Pipeline Design Characteristics of Some Industrial Paste-Like Slurries

G. Addie, M. Carstens, A. Sellgren, R. Visintainer, and L. Whitclock

There is a wide variety of industrial pastes or non-settling slurries pumped in mining, dredging and reclamation projects as products, refuse and tails.

Common types / names are:

→ alumina red mud

→ tar sands manure

→ tar sands

→ fly ash

→ phosphate clays

→ fine tails

→ (CT) consolidated clays

Non-settling slurries are formed by a mixture of fine solid particles and water in which the solid particles will settle very slowly.

Non-settling slurries flowing in a pipeline exhibit a nearly uniform distribution of particles across the flow section and an axisymmetric velocity distribution and are analyzed as a pseudo fluid having the specific gravity, Sm.

The pipeline performance or friction of these varies dramatically with the type, its concentration, and the particulars of the actual slurry making it difficult to select pumping equipment and to design associated pipelines.

The GIW Hydraulic Laboratory in Grovetown Georgia has tested a number of these slurries over the last 30 years for various mining customers.

Where available in the public domain and/or where permission has been obtained, the results of those tests are presented in this paper in a form usable for pipeline and pump system designers and users.

Small scale slurry testing can be accomplished in GIW's 3" closed slurry loop, shown here with a temporary section of 6" piping for a specialty test.

Testing within this type of loop is more economical and requires less material while generating test results scalable to the production pipe size.

GIW's largest closed slurry loop is currently comprised of 20" steel piping (yellow).

Water testing capabilities in excess of 100,000 gal/min can be achieved with the 48" steel pipe loop in conjunction with a 56,400 gallon sealed tank as shown here in blue.

All permanent GIW test loops are fed by centrifugal slurry pumps.

Specialty testing can be conducted with other pump types as illustrated here by a membrane positive displacement pump.

The objective in this paper is to present generalized pipeline loop friction loss results at various solids concentrations for a variety of non-settling fine-particle industrial slurries and briefly discuss the pumpability with centrifugal slurry pumps.

The pipeline friction loss evaluations are limited to laminar flows with the focus on pipeline scaling.

The pressure gradient, $\Delta p / \Delta x$ (Pa/m), for flow in a horizontal pipeline is:

$$\frac{\Delta p}{\Delta x} = \rho \cdot g \cdot j \qquad \text{(1)}$$

where:

   j   is the friction losses expressed in m of slurry per m of pipe,

   ρ is the density of the slurry,

   g   is the acceleration due to gravity (9.8 m/s2).

The slurry density ratio can be expressed as:

$$S_m = \frac{\rho}{\rho_O} = 1 + C(S_S - 1) \qquad ②$$

where :

ρ_o **is the density of water**

C   **is the solids concentration by volume calculated by:**

$$C = \frac{S_m - 1}{S_S - 1} \qquad ③$$

and:

$$S_S = \frac{\rho_S}{\rho_O} \qquad ④$$

where :

ρ_s **is the density of solids**

A force balance for the flowing slurry between two sections a distance Δx apart relates the pressure gradient, Δp/Δx and the friction loss gradient, j (eqn 1) to the pipeline wall shear stress, τ_0, through the following relationship:

$$\tau_0 = \frac{(\Delta p / \Delta x)D}{4} = \frac{\rho g j D}{4} \qquad (5)$$

where:

    D   is the pipeline diameter

Pipeline pumping design parameters can be calculated for particular flow rates and velocities with Equation 5 based on friction loss results expressed in terms of shear stresses.

In all fluids, internal shear stress, τ_0, is a function of the rate of strain.

In uniform flow in a pipe, the rate of strain is the velocity gradient, du/dr, in which:

  u = velocity at a point and
  r = the radius

For a Newtonian fluid flowing uniformly in a pipe:

$$\tau = -\mu \frac{du}{dr}$$

⑥

Equation 6 together with a similar force balance as in Equation 5 for a cylinder with radius r within the flowing fluid in the pipe results after integration and rearrangements (Wilson et al, 1997) in Equation 7 for the wall shear stress:

$$\tau_0 = \mu \left(\frac{8V}{D} \right)$$

(7)

where:
  8V/D   is the shear strain at the wall for a Newtonian fluid flowing at velocity V
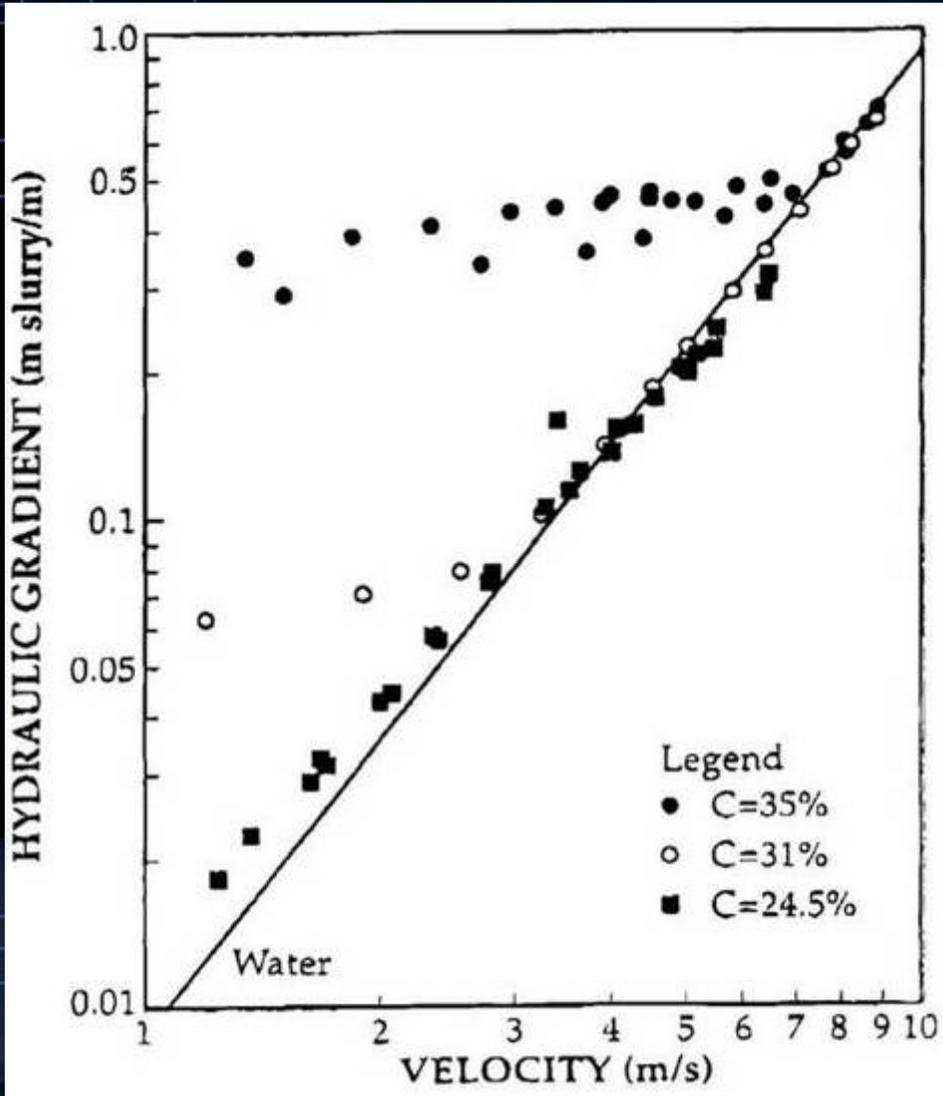
Figure 1 Typical Non-Settling Slurry

It can be seen in Figure 1 that for a typical non-settling slurry that, for the lowest density ratio, the flow behaves in a turbulent way following the water curve for the investigated velocities down to about 1.3 m/s. For flows at the higher concentrations, the slope is small and is typical of laminar conditions.

The value of du/dr, shear strain at the wall for non settling slurries, is no longer equal to 8V/D as expressed in eqn 7 for Newtonian fluids. The basis for the established technique by Rabinowitsch and Mooney (see for example Wilson et al,1997) to determine the shear strain for non-Newtonian fluids is to plot τ_0 versus 8V/D on log-coordinates

The local slope of this plot, n, is given by:

$$n = \frac{d(\ln \tau_0)}{d(\ln 8V/D)}$$

⑨
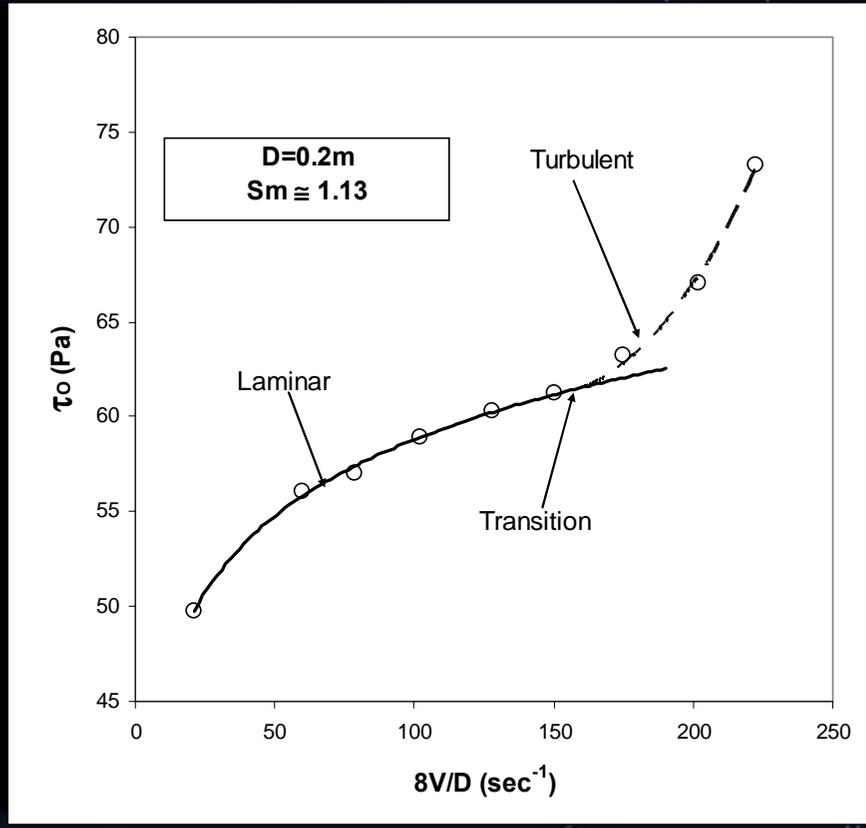
Figure 2. Scaling function of a clay-water slurry

As shown in Figure 3, where n is obtained over a considerable span. The rate of strain of a fluid particle adjacent to the pipe wall can then be expressed as:

$$-\frac{du}{dr} = \left(\frac{1+3n}{4n}\right)\left(\frac{8V}{D}\right)$$
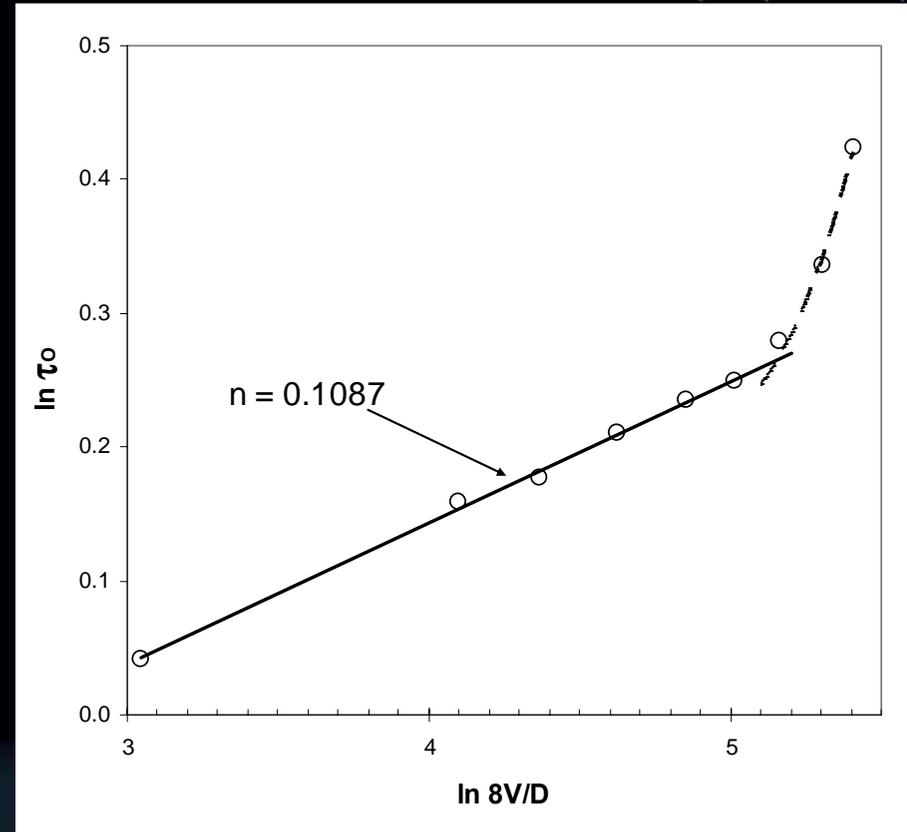
for all laminar flows in a pipe.

Figure 3. Graphical determination of n

This technique has been applied to the example in Figure 4 with n= 0.11 to obtain the shear strain. The relationship between shear stress and strain rate is known as a rheogram. The rheogram produced from the example in Figures 2 and 3 is shown in Figure 4.
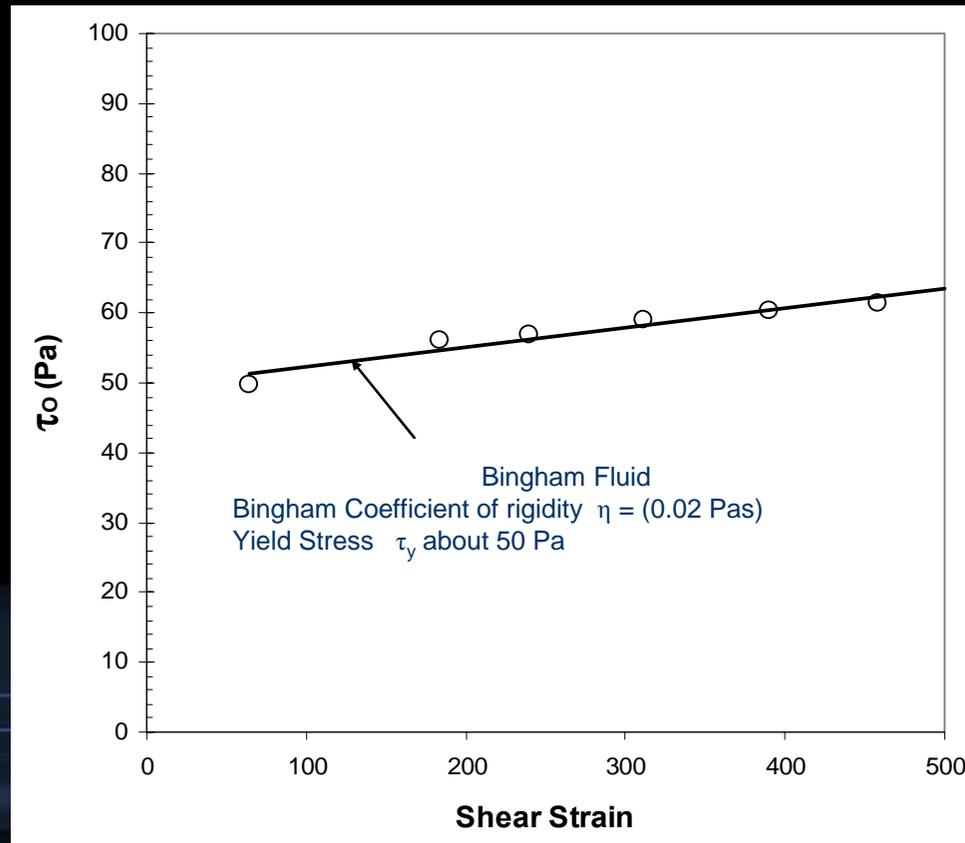
Figure 4. Rheogram of clay-water slurry

From this rheogram, the clay-water slurry closely approximates a so called Bingham fluid with a coefficient of rigidity, η of 0.02 Pas and a yield stress, τ_y of about 50 Pa. The Bingham model is expressed in the following way:

$$\tau = \tau_y + \eta\left(\frac{-du}{dr}\right)$$

The power law, or pseudoplastic model, is defined by:

$$\tau = B\left(\frac{-du}{dr}\right)^n$$

where:

B and n are the consistency and flow behaviour indexes, respectively.

In order to obtain scaling relationships, evaluated pipeline data for a variety of slurries and concentrations can be empirically fitted to Sm-1 and a constant B and n in an expression similar to eqn 12.

$$\tau_0 = B(8V / D)^n$$

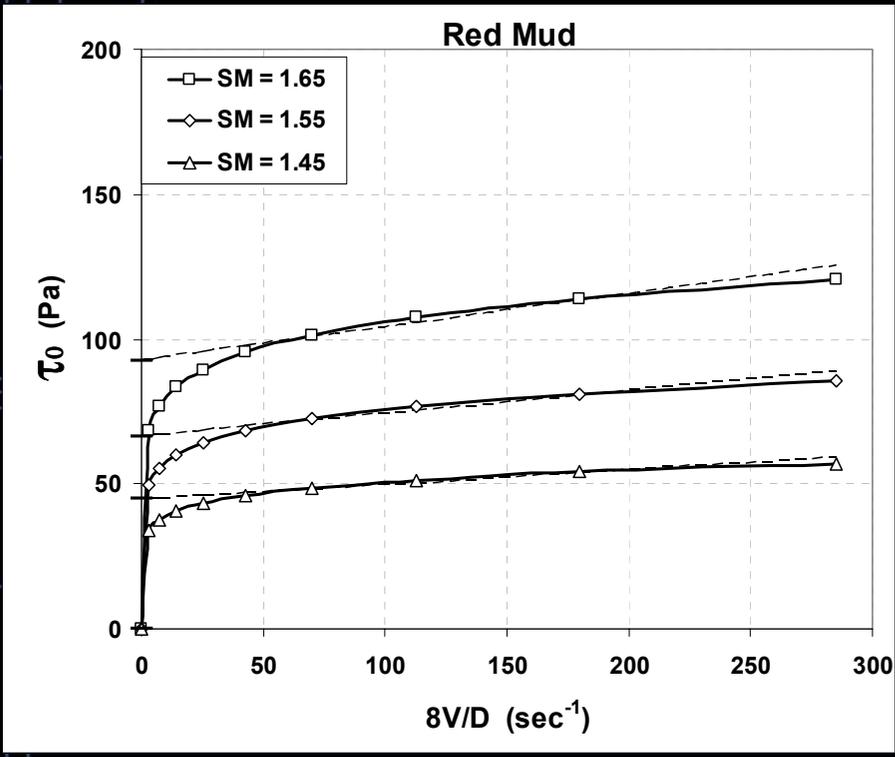Or simply plotted at the different concentrations of interest.

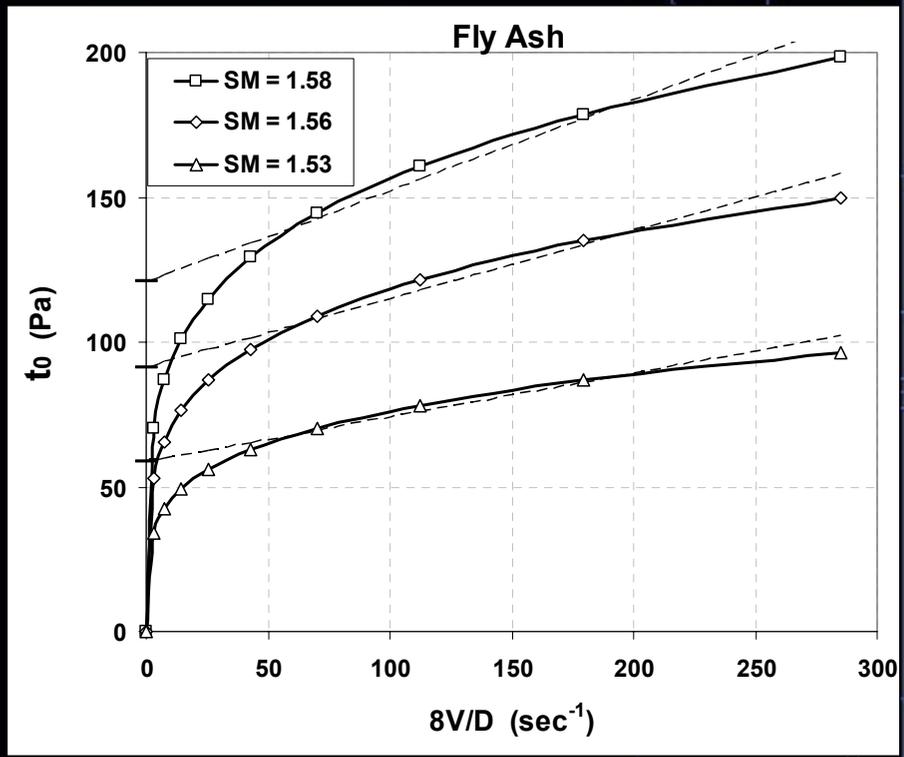Figure 6. Pipe wall shear stress versus 8V/D for the red mud at various concentrations

Figure 7. Pipe wall shear stress versus 8V/D for fly ash at various concentrations

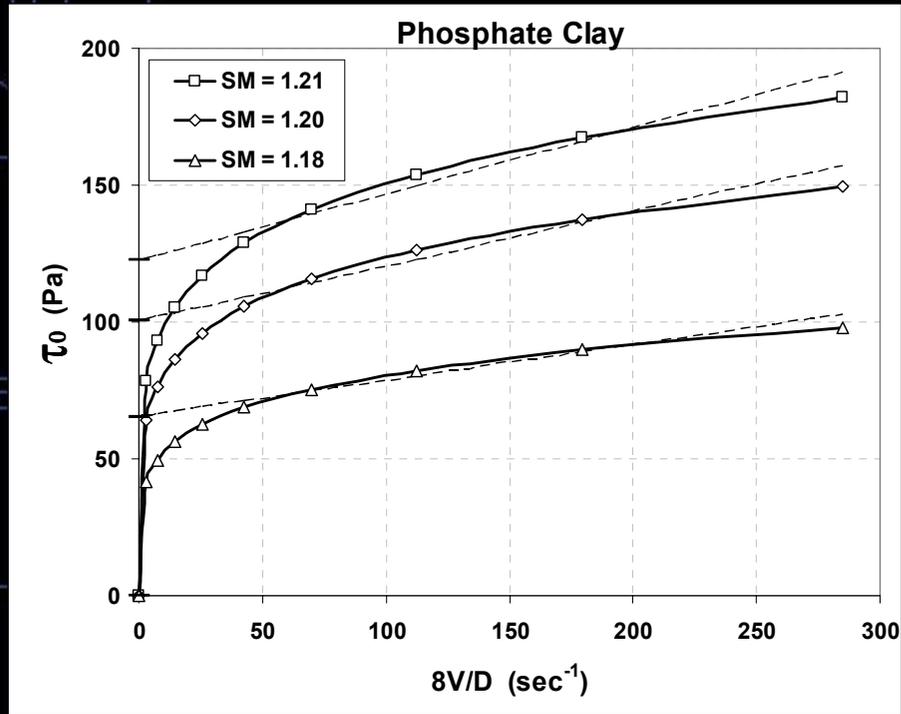**Figure 8. Pipe wall shear stress versus 8V/D for phosphate clay at various concentrations**
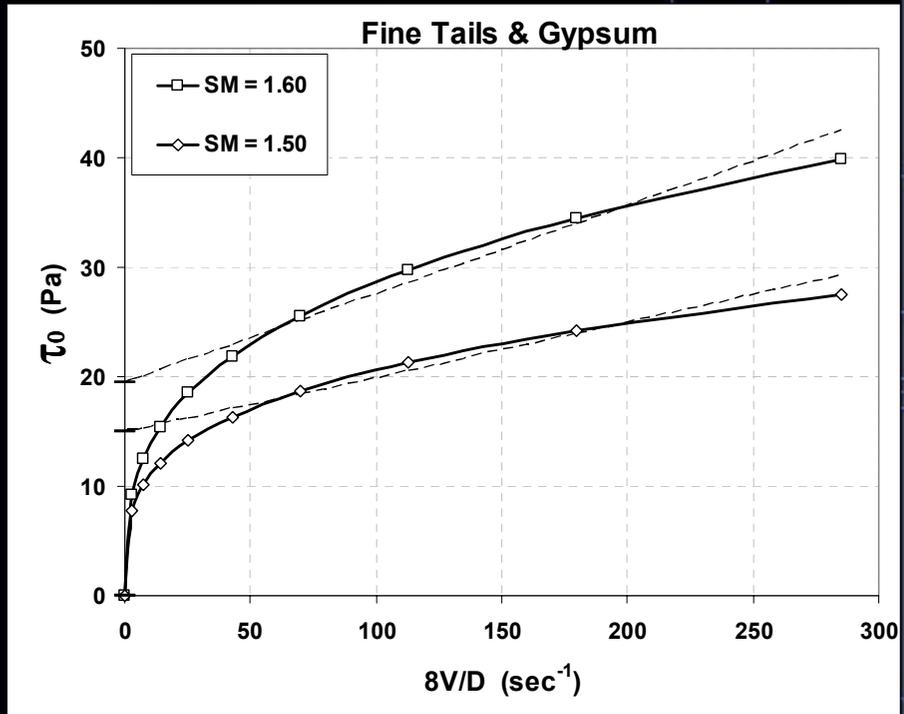
Figure 9. Pipe wall shear stress versus 8V/D for fine tails and gypsum at various concentrations
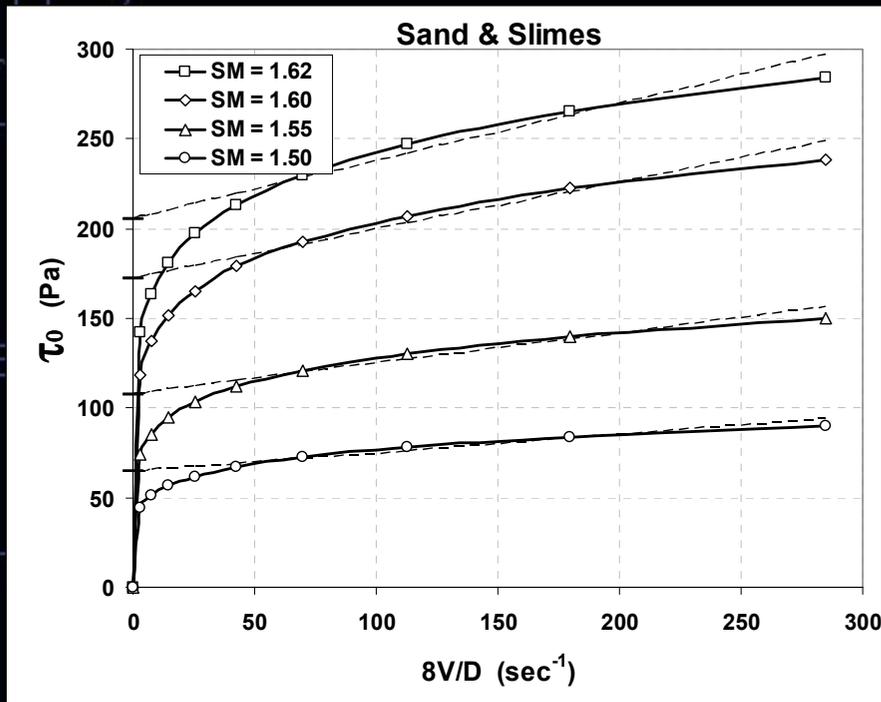
Figure 10. Pipe wall shear stress versus 8V/D for sand and slimes at various concentrations
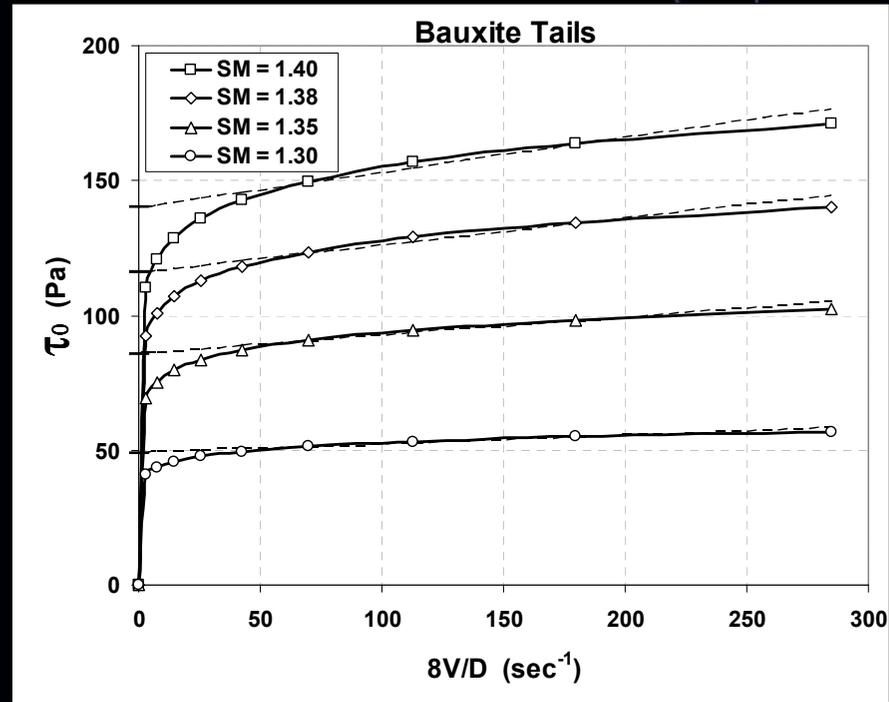
Figure 11. Pipe wall shear stress versus 8V/D for bauxite tails at various concentrations

Floor deposition test from 25mm hose

Trench deposition

DISCUSSION AND CONCLUSION

The designer and the owner of a pipeline-pumping system for a non-settling non-Newtonian slurry needs to obtain accurate friction loss values for the full-scale application at a range of operating conditions. The most reliable way to obtains this is to scale up experimental results directly with the scaling parameter 8V/D, based on data in a pipeline of reasonable size compared to the full size system.

A characteristic for all the tested slurries is the sensitivity of the friction losses to the solids content with dramatically increased losses beyond a certain concentration for a small increase in slurry density.

Variable speed operation for laminar flows and tight density control are recommended for centrifugal pumps.

The yield stress is a key parameter in the design and operation of high density thickening systems. If one parameter was to be considered as representative of the slurries investigated here, then the effective zero velocity yield stress would be that value that tells most about a given non-settling slurry.
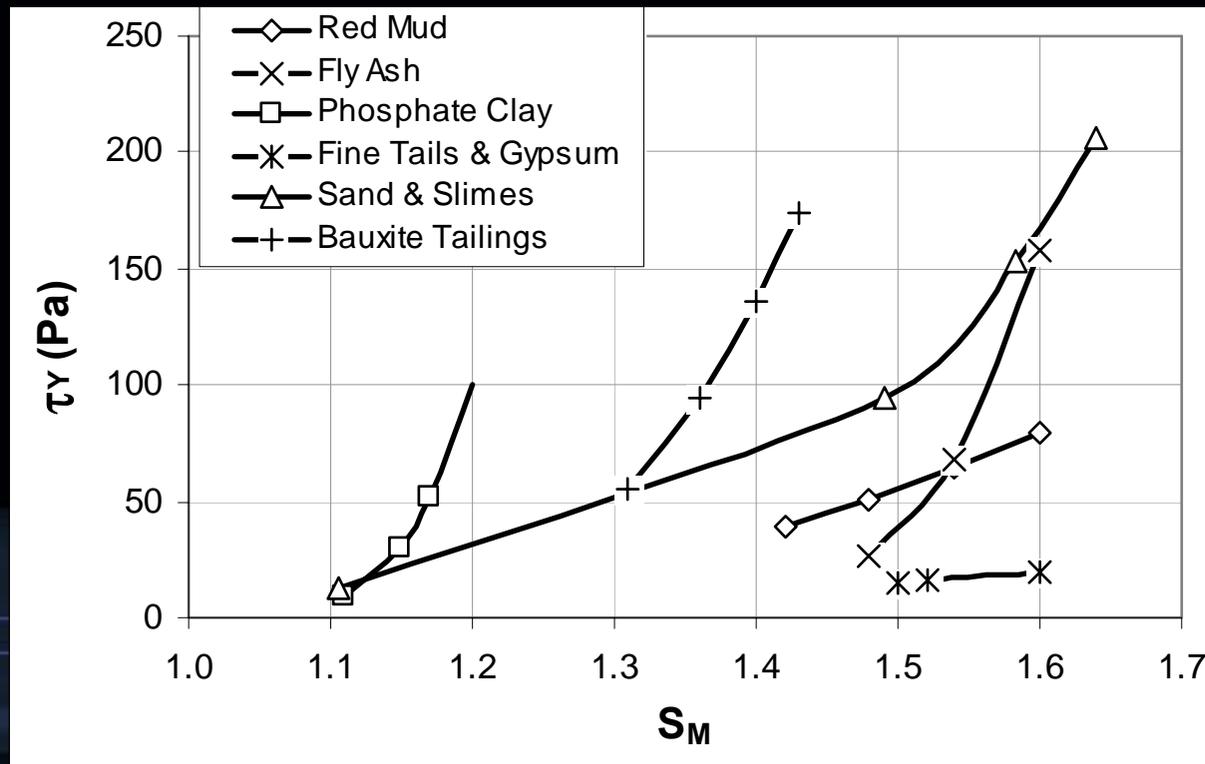

Figure 12. Summary of estimated yield stresses for data shown in Figs. 6 to 11 for the investigated products

Where it is not possible to get enough sample to carry out pipeline tests, a simple test designed by the principle author may be helpful.

As in the picture below a wooden pencil is stuck vertically in a sample in a beaker.

If the pencil falls over, the slurry will likely be pumpable using centrifugal pumps and have shear mess less than 100 Pa.

If it holds firm vertical it will be difficult or impossible to pump.

Figure 13- Pencil test for slurry pumpability