Slurry handling

Factors influencing slurry rheology

In this article from Algeria, A. Benretem with co-authors M. Benidir and R. Chaib discuss their study of the rheological behaviour of water-phosphate slurries containing various concentrations of solid particles. The influence of particle size, particle size distribution and concentration on the mixture’s transport velocity and viscosity are examined.

In a mixture composed of solid particles suspended in a liquid, the combination of the type, size, shape and quantity of the particles together with the nature of the transporting liquid determines the exact characteristics and flow properties of the slurry. Non-settling mixtures contain very fine particles which can form stable homogeneous systems exhibiting increased apparent viscosity. These mixtures usually have low wear properties but require very careful consideration when selecting the correct pump and drive as they often do not behave in the manner of a pure liquid. When fine solids are present in the mixture in sufficient quantity to cause deviation in behaviour from that of a pure liquid, the system is referred to as non-Newtonian. Settling mixtures are formed by coarser particles and tend to form an unstable system. Therefore, particular attention must be given to flow and power calculations in these cases. These coarser particles tend to have higher wear properties and form the majority of mixtures encountered in real applications. This type of mixture is also referred to as heterogeneous.

Critical carrying velocity

Particles have a tendency to settle when a mixture is conveyed by the flow through a pipe. The critical velocity for slurry flow in a pipe is the velocity at which particles start forming a sliding bed on the bottom of the pipe. This will cause the flow to become unstable and the pipe will eventually clog. General slurry pipeline practice is to design the pipe velocity to exceed the critical velocity by at least 30%. This pipe velocity will depend upon the diameter of the pipe, the concentration of solids, and the properties of the fluid and solid particles. To prevent settling in the pipeline, the hydraulic conditions within a slurry pipeline should ensure turbulent flow.

There are Newtonian and non-Newtonian fluids based on the constitutive equations. For fluids, the apparent viscosity, \( \eta \), is defined by:

\[
\eta = \tau / \dot{\gamma}
\]

where \( \tau \) is the shear stress and \( \dot{\gamma} \) the shear rate.

The apparent viscosity \( \eta \) is a useful parameter. In the case of Newtonian fluids, \( \eta \) is constant. For non-Newtonian fluids, \( \eta \) is variable, which means that the shear stress \( \tau \) varies with the shear rate \( \dot{\gamma} \).

Figure 1. Shear stress versus shear rate curves for time-independent non-Newtonian mixtures.
Most semi-solids such as mineral slurries, whether found in nature or synthesized in a laboratory, exhibit non-Newtonian fluid behaviour\(^1\text{–}^3\). The information for characterizing the rheology of time-independent non-Newtonian mineral slurries is summarized in Figure 1. However, time-dependent non-Newtonian fluid behaviour is usually encountered in fine and concentrated solid suspensions\(^4\text{–}^5\). Such fluids are characterized by a change in viscosity with time at a constant shear rate.

It is known that the settling speed of the solid particles in the liquid plays a very significant role in the hydraulic transport of solid-liquid mixtures. Generally, the size and shape of the solid particles, and the density and properties of the transporting fluid are considered to be significant parameters. Several studies of this subject have been carried out\(^6\), leading to empirical relationships to determine the terminal velocity, \(v\), in m/s:

\[
v_t = 134.14(d_{50} - 0.039)^{0.972}
\]

(2)

This equation is largely used because of its simplicity. It requires only the knowledge of the median grain size \((d_{50})\) in millimetres. Swamee and Ojha\(^7\) derived an empirical equation for the terminal velocity of non-spherical particles. The proposed expression for terminal velocity is:

\[
W_s^* = \left[\frac{4.84d_{50}^{0.83}}{(1 + 4.5\beta^{0.6})^{1.1}}\right]^{0.794} \left[\exp(2.4\beta^{0.4}) - 1\right]^{0.125}
\]

(3)

with the following non-dimensional parameters:

\[
W_{s}^* = \frac{v_t}{\sqrt{\rho_o - 1}g d_{50}}
\]

(4)

\[
U^* = \frac{d_{50}}{\sqrt{\rho_s - \rho_o}}
\]

(5)

where \(W_s^*\) is the non-dimensional settling velocity and \(U^*\) the fluid kinematic viscosity.

\(d_{50}\) is the nominal diameter of the solid particle in metres. It is the diameter of a sphere having the same volume \(V\) as the given particle and is defined by:

\[
d_{50} = \left(\frac{6V}{\pi}\right)^{1/3}
\]

(6)

\(\beta\) is the Corey shape factor, which is defined as:

\[
\beta = \frac{c}{2ab}
\]

(7)

where \(c\) is the minimum dimension of the particle (in metres), \(a\) the maximum dimension and \(b\) the intermediate dimension.

The equation is valid for any diameter and density of the solid \(\beta\) particles. Equation 3 is very simple; but it has some consequences and limitations, namely, the size of the solid particles is restricted to a maximum of 2 mm and their density must be close to that of sand.

**Factors affecting mixture viscosity**

**Particle size distribution**

The geometry of the solid particles can only be given for regular shapes. For irregular particle shapes such as is the case for mineral fragments, experimental or statistical methods have been employed to determine volume or surface. The equations for speed and drag coefficients were deduced for spheres; therefore it is most convenient to express the geometry in terms of equivalent and effective sphere diameter. The equivalent diameter of a particle is defined as the diameter of a sphere with the same volume as the particle. The effective diameter is defined as being the diameter of a sphere with the same transport velocity as the particle; it is determined by measuring speed in experiments. The calculations of the sphere diameter and velocity are determined by the laws of Stokes and Newton.

A general recommendation is to maintain flow velocity at about 30% above the critical sedimentation velocity. A study performed by Durand on sand-water slurries\(^8\) provides the following formula for determining critical velocity:

\[
v_C = \sqrt{\frac{2g}{\beta v_{cr}} \left(\frac{\rho_s - \rho_o}{\rho_o}\right)}
\]

(8)

where \(v_{cr}\) is the critical carrying velocity; \(\beta v_{cr}\) is the coefficient dependent upon particle size and concentration; \(S\) is the concentration; \(\rho_s\) the density of the solid and \(\rho_o\) that of water.

For a given material, the equivalent diameter is a function of the volume of the irregular particle. All the particles with a given volume will have the same equivalent diameter. The effective diameter, in addition, is also influenced by the shape of the particles. Particles with the same volume but different shapes can have different speeds and consequently varying effective diameters. Since transport speed has a significant influence on the behaviour of the mixture, the effective diameter is considered to be the preferred parameter.

The concentration versus particle size curve shown in Figure 2 has the shape of a normal distribution curve. The majority of the solid particles in the phosphate mixture (with density \(\rho_s = 2.8\text{ t/m}^3\)) have a particle diameter of about 0.2 mm to 0.4 mm, with the average size (mode) being 0.2 mm.

**Experimental study**

Hydraulic calculations for a phosphate slurry pipeline depend on the conditions under which the mixture moves in the pipes and on its mechanical properties, which are influenced by various factors, mainly the concentration and size distribution of the phosphate particles. To design pipelines for transporting phosphate slurries, we must therefore establish the optimal size characteristics of the particles, enabling the water-phosphate mixture to be pumped at high concentration with minimal energy losses and ensuring high stability.

To study the effects of various factors on the mechanical properties of mixtures, experiments were carried out in the laboratory. Theses concerned the effect of the phosphate characteristics and the concentration of the mixture on the viscosity. Particular attention was paid to particles smaller than 0.4 mm at various concentrations.
Rotary viscosimeters were used to obtain rheological curves for mixtures with different size classes of phosphate over a range of concentrations. Figure 3 is a plot of the viscosity of the mixture according to volumetric concentration, S. It can be seen that viscosity, \( \eta \), increases with the mixture concentration, with some critical concentration being observed, above which the viscosity increases far more rapidly. This critical concentration is characterized not by an individual point, but by a zone beginning at the point at which the \( (\eta, S) \) curve deviates from a straight line. It can also be seen that the curve for a mixture containing phosphate particles of the 0–0.2 mm class is quite separate from the curves of the other mixtures.

Effect of mixture concentration

It is therefore of interest to study how the rheological characteristics depend on the concentration of different size classes in the mixture. Figure 4 is a plot of the viscosity versus size class at different concentrations, S.

It can be seen that the value of \( \eta \) increases markedly with decreasing particle size. As the mixture concentration increases, the point of marked change on the rheological characteristics is displaced towards larger particles. For mixtures of concentration 15–20%, a predominant effect on the viscosity is exerted by particles smaller than 0.3 mm; at the same concentrations the presence of coarser particles in the mixture has virtually no effect on the rheological properties.

With increasing concentration, the size of the solid particles exerts a predominant effect on the rheological properties of the mixture. For solid particles with diameters less than 0.2 mm a steep increase in viscosity is observed, but for solid particles having a diameter greater than 0.2 mm, the viscosity increase is less rapid.

Conclusion

The results of the study indicate a range of rheological behaviours depending on solids content, particle size distribution and phosphate type. Firstly, there is a zone of critical concentrations at which the rheological characteristics of a mixture increase markedly. Secondly, the critical zone for fine particles corresponds to lower concentrations. And finally, the maximum effect on the rheological properties of a mixture is exerted by particles smaller than 0.3 mm in diameter. The addition of coarser particles does not have a marked effect on the mechanical properties of a mixture.

References


Contact

A. Benretem
Laboratory of Electromechanical Systems
Bajd/Mejdahir University
Annaba, Algeria
Tel/Fax: + 213 38 87 11 68
E-mail: Benretem_al@yahoo.fr

M. Benretem and R. Choub
Laboratory of Mechanics
Mentouri University
Constantine, Algeria