Demonstration of Mixing and Transferring Settling Cohesive Slurry Simulants in the AY-102 Tank - 12323

Duane J. Adamson* and Phillip A. Gauglitz **
*Savannah River National Laboratory, Aiken, South Carolina 29808
**Pacific Northwest National Laboratory, Richland, Washington 99352

ABSTRACT

In support of Hanford's feed delivery of high level waste (HLW) to the Waste Treatment and Immobilization Plant (WTP), pilot-scale testing and demonstrations with simulants containing cohesive particles were performed as a joint collaboration between Savannah River National Laboratory (SRNL) and the Pacific Northwest National Laboratory (PNNL) staff. The objective of the demonstrations was to determine the impact that cohesive particle interactions in the simulants, and the resulting non-Newtonian rheology, have on tank mixing and batch transfer of large and dense seed particles. The work addressed the impacts cohesive simulants have on mixing and batch transfer performance in a pilot-scale system. Kaolin slurries with a range of wt% concentrations to vary the Bingham yield stress were used in all the non-Newtonian simulants. To study the effects of just increasing the liquid viscosity (no yield stress) on mixing and batch transfers, a glycerol/water mixture was used. Stainless steel 100 micron particles were used as seed particles due to their density and their contrasting color to the kaolin and glycerol.

INTRODUCTION

In support of Hanford's waste certification and delivery of tank waste to the Waste Treatment and Immobilization Plant (WTP), Savannah River National Laboratory (SRNL) was tasked by *Washington River Protection Solutions* (WRPS) to evaluate the effectiveness of mixing and transferring tank waste in a Double Shell Tank (DST) to the WTP Receipt Tank. The work addresses the impacts cohesive simulants have on mixing and batch transfer performance [1]. This work is follow-on to the previous tasks "Demonstration of Mixer Jet Pump Rotational Sensitivity on Mixing and Transfers of the AY-102 Tank" [2] and "Demonstration of Simulated Waste Transfers from Tank AY-102 to the Hanford Waste Treatment Facility" [3]. The cohesive simulants were investigated and selected jointly by SRNL and PNNL and a white paper was written on this evaluation [4]. The testing and demonstrations of cohesive simulants was a joint effort performed as collaboration between SRNL and PNNL staff.

The objective of the demonstrations was to determine the impact that cohesive particle interactions in the simulants have on tank mixing using the 1/22nd scale mixing system and batch transfer of seed particles. Seed particles are particles of contrasting color added to the mixing tank to aid visual observations of mixing and as an indicator of how well the contents of the tank are mixing. Also, the seed particles serve as a measuring stick for how well the contents of the tank are transferred from the mixing tank during batch transfers. This testing is intended to provide supporting evidence to the assumption that Hanford Small Scale Mixing Demonstration (SSMD) [5] testing in water is conservative.

EXPERIMENTAL METHOD

The test system used for the mixing and batch transfer demonstrations is shown in Figure 1. The transparent 1/22nd Mixing Demonstration Tank (MDT) has an ID of 103 cm and a height of 76.2 cm with a transparent bottom for visual observations of mixing from the underside. The geometrically scaled obstructions consisted of 22 Air Lift Circulators (ALC), a heating coil, a transfer pump feed line and two 1/22nd scaled Mixer Jet Pumps (MJPs). The geometrically scaled obstructions simulated the obstructions found in the Hanford AY-102 Tank. The obstructions were installed in the MDT for the cohesive simulant testing and demonstrations.

Only one slurry pump (Pump 1) was used to feed the two MJPs. The slurry pump was located external to the MDT and the flow rate to each MJP was controlled by a variable speed drive on the slurry pump. The test fluid (simulant) was pumped from the MDT through the inlet at the very bottom of the MJPs to the slurry pump and then circulated back to the MJP down to the jet nozzles. The simulant in the MDT mixed when the fluid flowed out of the two nozzles on each MJP.

The 329 L of simulant in the MDT was mixed using only the two scaled, rotating MJPs. The MJP's were operated either at 37.8 L/min (10.0 gpm) resulting in a jet nozzle velocity of 8.5 m/s (28 ft/s) or 30.3 L/min (8.0 gpm) resulting in a jet nozzle velocity of 6.8 m/s (22.4 ft/s). Each test consisted of six batch transfers to individual Receipt Tanks (RTs). The contents of the MDT were mixed for approximately 30 minutes with the MJPs at the specific test condition before the making the first batch transfer.

The batch transfers from the MDT were made with a progressive cavity pump (Pump 3). Six individual 54 L batch transfers were made to the RTs via pumping the simulants at 2.2 L/min resulting in a suction velocity of 1.2 m/s. Once the simulant was pumped to the RTs, the consistency of solids in each batch was compared.

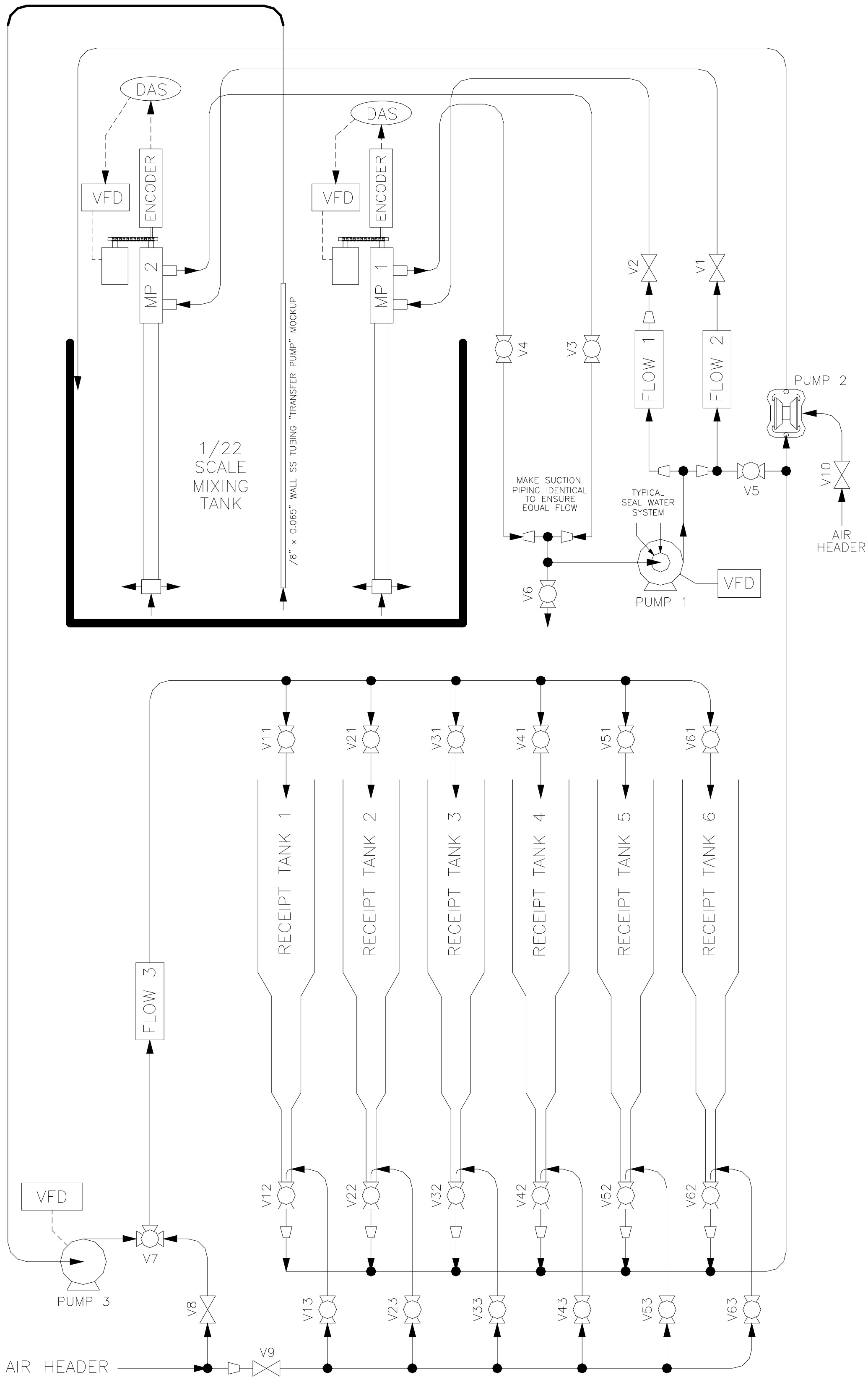

Figure 1: Drawing of the Mixing/Transfer Demonstration System

The residence time of the system was approximately 5.5 minutes (329 L in MDT, MJP operating at 30.3 L/min), allowing five tank volumes of slurry to flow through the mixer pumps during this 30-min period. This is in contrast with the residence time of the full-scale AY-102 Tank which is approximately 45 minutes (million gallon tank). The residence time of the 1/22nd scale was one of the scaling concerns from the full scale AY-102 Tank.

Once the transfers were made by pumping the simulants from the MDT to the six RTs, the consistency in the amount of seed particles in each batch was compared. Tests were conducted with non-Newtonian cohesive simulants with Bingham yield stresses (YS) ranging from 0.3 Pa to 7 Pa. Kaolin clay and 100 micron Stainless Steel (SS) seed particles were used for all the non-Newtonian simulants. To specifically determine the effects of the yield stress on mixing and batch transfer, tests were conducted with a Newtonian mixture of glycerol and water mixed to a viscosity of 6.2 cP, which was selected to match the Bingham consistency (high shear rate viscosity) of the higher yield stress kaolin slurries. The water/glycerol mixtures used the same 100 micron SS seed particles.

RESULTS AND DISCUSSION

Nine mixing and transfer demonstrations were conducted in the 1/22nd pilot-scale Mixing/Transfer Demonstration System (Test 5 was repeated). Table I is the test matrix for the demonstrations. As stated earlier, the batch transfer flow rate parameter was held constant at 2.2 L/min for all demonstrations. The continuous transfer was conducted by continuously operating the MJPs and slurry transfer pump while not allowing the MDT contents to settle between batches. Once a batch of 54.1 L was transferred to a RT, the valve line up was changed, sending the subsequent batch to the next RT.

To eliminate cohesive particle interactions effects in Test 5, Test 5A was developed using Tetra-Sodium PyroPhosphate (TSPP). TSPP is a known dispersant for the clay particles and has been shown to reduce, or even eliminate, the yield stress of kaolin slurries [6,7]. One mechanism described for the role of TSPP is that the phosphate group will adsorb onto the kaolin particle surfaces, make that portion of the kaolin particle negatively charged, and thereby increase the overall repulsion between kaolin particles [6]. The increased particle repulsion weakens the floc structure and thus reduces or eliminates the yield stress. At the end of Test 5, TSPP was added in the RTs and the simulant was pumped back to the MDT to conduct Test 5A. The resulting data was used to compare the mixing and batch transfer results for the exact simulant used in Test 5, but with the cohesive particle interactions eliminated by the addition of 600 ppm of TSPP.

Table I: Test Matrix for Cohesive Simulant Demonstrations

Test #	Simulant	Batch Transfer (lpm)	Transfer Type	Mixer Jet Pumps		
				Rotation (rpm)	Flowrate (lpm)	Velocity (m/sec)
1	Water with 5 wt% SS seeds	2.2	Continuous	1.6	37.8	8.5
2	14 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	30.3	6.8
3	14 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	37.8	8.5
4	23.4 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	30.3	6.8
5	23.4 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	37.8	8.5
5A	23.4 wt% Kaolin 5 wt% SS seeds + TSPP	2.2	Continuous	1.6	37.8	8.5
6	52 wt% Glycerol 5 wt% SS seeds	2.2	Continuous	1.6	30.3	6.8
7	52 wt% Glycerol 5 wt% SS seeds	2.2	Continuous	1.6	37.8	8.5
8 [a]	19 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	30.3	6.8
9 [a]	19 wt% Kaolin 5 wt% SS seeds	2.2	Continuous	1.6	37.8	8.5

[a] - Pre-layered bed of 5 wt% SS (17.3 Kg of SS in a thin layer of 1.5 Pa kaolin) in the MDT

Table II lists the rheology results of the simulants tested. The non-Newtonian simulants tested had yield stresses that ranged from 0.3 Pa to 7.0 Pa. The 52 wt% glycerol/water mixture had a viscosity that was closest to the high shear rate viscosity of the 19 wt% and 23.4 wt% kaolin slurries. The 23.4 wt% kaolin with 600 ppm TSPP has a constant viscosity that was slightly higher than water, but well below the high shear rate viscosity of the 23.4 wt% slurry without TSPP.

Table II: Rheology Results for Simulants

	Simulant	Bingham Yield Stress, Pa	Viscosity/Bingham Viscosity, cP
Test 1	Water + 5 wt% SS	0	1
Test 2	14 wt% Kaolin + 5 wt% SS, (8 hr)	0.3	3.4
Test 3	14 wt% Kaolin + 5 wt% SS	0.3	3.4
Test 4	23.4 wt% Kaolin + 5 wt% SS, (4 hr)	7.0	9.1
Test 5	23.4 wt% Kaolin + 5 wt% SS, (15 min)	6.4	8.3
Test 5A [a]	23.4 wt% Kaolin + 5 wt% SS + TSPP	0	1.9
Test 6	52 wt% Glycerol + 5 wt% SS	0	6.2 @ 21˚ C
Test 7	52 wt% Glycerol + 5 wt% SS	0	6.2 @ 21˚ C
Test 8	19 wt% Kaolin, 5 wt% SS settled bed, (8 hr)	1.6	4.2
Test 9	19 wt% Kaolin, 5 wt% SS settled bed, (12+ hr)	1.9	4.5

[a] - Same as Test 5 except for 600 ppm TSPP added to batch

The SS mass was the same in all batch recipes, equating to 5 wt% in water. The SS particles ranged from 75 µm to 106 µm based on the vendor-supplied particle size distribution (PSD). These particles were used as seed particles in all testing. The advantage of using SS is that the particles are very dense (8,000 kg/m^3), making them difficult to suspend in the entraining fluid. Because these particles are not easily suspended under the planned test conditions, they are suitable for observing changes in mixing behavior with the different simulants. The SS particles can be seen visually in the kaolin during mixing; allowing their suspension off the bottom of the MDT to be observed visually, and their dark color during the batch transfers contrasts well.

Figure 2 shows the SS (dark color) settled to the bottom of the Receipt Tanks for Test 5. This picture is an example of how the seed particles were measured for each transfer demonstration. The picture on the right is a close-up of the settled SS in RT-3 from Test 5. The measuring scale in the picture is in inches.

Figure 2: SS Settled to Bottom of RTs, Test 5

Table III gives the measured height of the SS settled to the bottom of each Receipt Tank for each demonstration. For tests using 19 wt% and 23.4 wt% kaolin simulants, which have a sufficient yield stress to stop the settling of the SS seed particles, TSPP was added in the RTs after the transfers were completed to eliminate the yield stress of the slurry and allow the SS seed particles to settle quickly to the bottom of the Receipt Tanks. TSPP contaminated slurries were not reused except for Test 5A.

Table III: SS Transferred to Receipt Tanks

	RT-1 cm	RT-2 cm	RT-3 cm	RT-4 cm	RT-5 cm	RT-6 cm
Test 1	17.1	17.1	17.1	17.8	18.4	21.6
Test 2	19.7	19.7	19.7	19.7	19.7	19.7
Test 3 [b]	17.3	22.2	19.7	20.3	19.7	7.6
Test 4 [b]	34.0	31.8	30.3	28.3	24.8	20.3
Test 5 [b]	34.9	31.1	32.5	31.8	34.0	24.0
Test 5A	18.4	22.5	20.3	21.9	20.3	23.5
Test 6	15.2	15.2	16.2	17.8	17.8	21.6
Test 7	23.0	24.8	22.7	21.9	18.9	27.3
Test 8 [b]	27.0	26.0	24.8	25.7	24.9	19.7
Test 9 [b]	29.1	29.7	31.8	30.3	29.2	21.0

[b] - TSPP added to receipt tanks

The tests with the higher yield stress had the most effective batch transfers of SS solids out of the MDT; Tests 4 (23.4 wt%/SS), 5 (23.4 wt%/SS), 8 (19 wt%/SS) and 9 (19 wt%/SS).

The data in the table shows that batch transfer of solids was less effective when only water was used as the carrier fluid. As the wt% of kaolin was increased (increasing the YS of the batch) the efficiency of transferring solids increased. This suggests that when testing with water as the carrier fluid, the water testing is conservative (when evaluating the transfer of solids) compared with a carrier fluid with a yield stress, which is more efficient transferring solids. The conclusion from this data, that water always transfers less seed particles, is conservative by this metric when compared to fluids with a higher yield stress and/or higher viscosity at the same mixing/transfer parameters.

As the yield stress of the slurry increases the observed mixing in the MDT decreases. However, as stated above, the total batch transfer of seed particles always increased with an increase of yield stress. Comparing Test 5 to Test 5A, where the only difference in the two tests was the 600 PPM of TSPP which reduced the yield stress to water (YS= 0) in Test 5A, there was significantly more seed particles transferred in the first five batches of Test 5, where the simulant had a yield stress (YS = 6.4 Pa). When mixing slurries with MJPs, it is more difficult to suspend particles from the tank bottom with increasing yield stress, but the particles stay suspended to a greater degree once lifted from the tank bottom. The combined effect of increasing the yield stress is an increase in the transfer of seed particles.

At the end of the six batch transfers there was always at least 0.6 cm to 1.3 cm (¼" to ½") of slurry left in the MDT with solids in the two dead zones (occurring at maximum distance from MJP center lines). Due to the poor mixing when the MDT liquid level drops to about 5.0 cm, there would always be a small amount of solids left at the bottom of the MDT, usually the larger, denser SS particles that could be seen from the underside of the tank.

The extreme poor condition (where most of the seed particles are not transferred to the RTs) of solids left in the MDT dead zones at the end of the transfers occurred with 5 wt% SS particles in water. The poor mixing that the carrier fluid (Test 1, water) created, allowed two large dead zones of particles to form. At the other extreme of seed particles being transferred from the MDT to the RTs occurred with a simulant with a high yield stress such as Test 5 (YS= 6.4 Pa). At the end of the transfer of Test 5 there were no visual signs of SS in the two dead zones.

The primary purpose of conducting tests with glycerol/water mixtures (Test 6 and Test 7) was to compare mixing and batch transfer results between water and cohesive slurries with a similar viscosity. It was found the higher viscosity of glycerol had a small improvement on the transfer of solids when compared to the water/SS at the same MJP flow of 37.8 lpm. Testing suggests that the higher viscosity of the carrier fluid improved the transfer of solids when compared to water. The testing also suggests that water is conservative (less SS seed particles transferred) when compared to a carrier fluid with a greater viscosity. Using a simulant with a greater viscosity would result in a better transfer of solids when the mixing/transfer parameters are the same.

The yield stress in the slurry affects the suspension and settling of the SS seed particles and the overall fluid motion in a number of ways. It is desired to quantify how broadly the results obtained in this study can be applied to the full-scale mixing behavior of DST waste with cohesive slurries that exhibit a yield stress. Dimensional analysis is a useful tool for making this evaluation. Previous studies have applied dimensional analysis to jet mixing of DSTs with horizontal jets (Bamberger et al. 1990 [8]) and the similar problem of vertical pulsed jets (Meyer et al 2009 [9], Bamberger et al. 2005 [10]). There are a number of dimensionless parameters that are identified, but for this evaluation we will focus on how switching from a Newtonian liquid to non-Newtonian fluid that follows the Bingham model changes the analysis.

In dimensional analysis, the choice of the specific dimensionless numbers to use is not unique. For evaluating particle settling behavior in a Newtonian fluid, a common dimensionless group to use is the Archimedes number given in Equation 1.

$$Ar = g d_p^3 \rho_l (\rho_p - \rho_l)/\mu^2 \qquad \text{(Eq. 1)}$$

In comparing Newtonian and Bingham fluid models, the Newtonian fluid is characterized by a single parameter, the viscosity, while the Bingham fluid has two parameters – the yield stress and consistency (plastic viscosity). Applying dimensional analysis, one additional dimensional group is needed to describe the behavior of a Bingham fluid in comparison to a Newtonian fluid. Again, the selection of dimensionless groups is not unique and for this evaluation we will replace the Archimedes number with yield Reynolds number (Equation 3) and the gravity yield parameter shown in Equation 3.

$$\text{Yield Reynolds Number} – Re_\tau = \rho U_j^{\,2} / \tau_y \qquad \text{(Eq. 2)}$$

$$\text{Gravity Yield Parameter} – Y_G = \tau_y / g(\rho_p - \rho_l) d_p \qquad \text{(Eq. 3)}$$

The yield Reynolds number is typically used to quantify the size of a cavern, which is defined as a region where the jet causes fluid motion, but outside of which the Bingham fluid remains stagnant due to the yield stress. The gravity yield parameter is often used to quantify the transition between particles that will sink due to gravity in a fluid with a yield stress or not.

Figure 3 is a plot of gravity yield parameter (Y_G) vs. yields Reynolds number (Re_τ) that shows the four general regions of behavior. In this plot, one can determine if a cavern exists in a slurry or if solids will settle. The vertical line, $Y_G = 0.06$, is based on experimental results (Chhabra 1993) [11]. The horizontal line distinguishing between a cavern being present at low Re_τ and the jet causing fluid motion throughout the vessel needs to be determined either theoretically or experimentally. In this study, we used the visual observations of the experiments, described below, and determined that cavern formation occurs at Yield Reynolds Numbers less than 30,000.

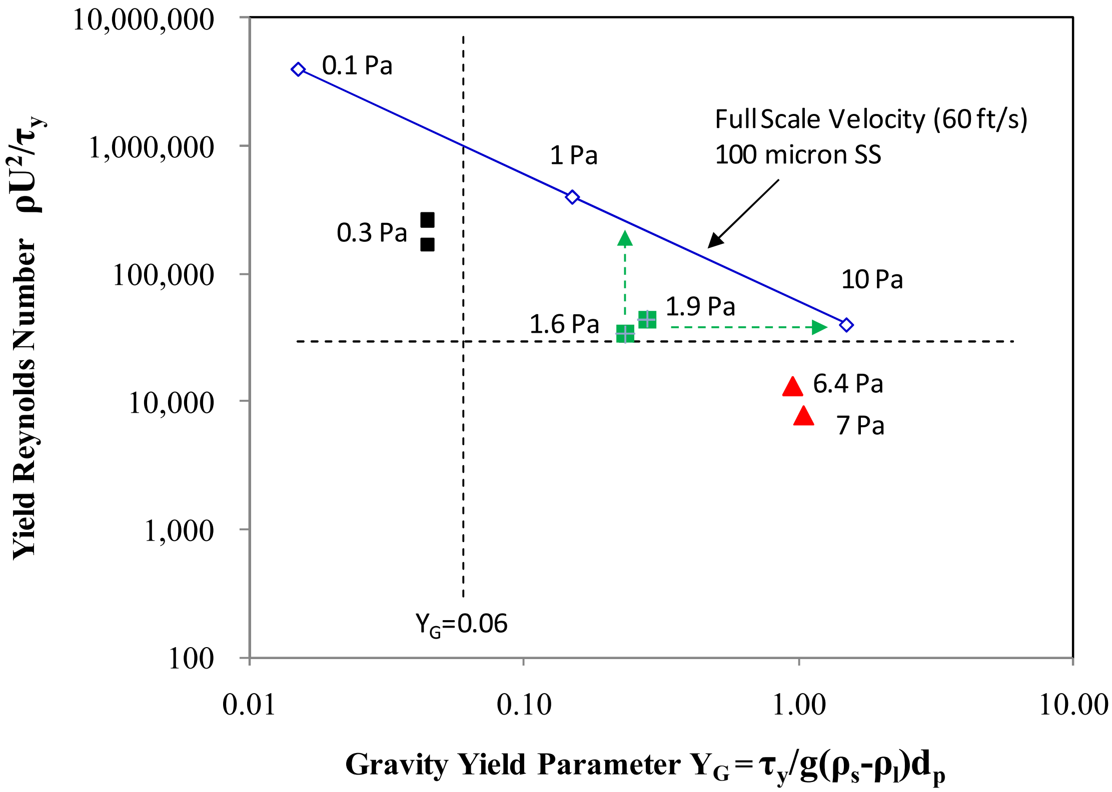

Figure 3: Gravity Yield vs. Yield Reynolds Number

The experimental visual observation is shown on the plot indicating that when Re_T is less than 30,000 a cavern will exist. When Re_T is increased above 30,000, the turbulent mixing and jet inertial forces will mobilize the vessel contents, and thus no cavern is formed. For particle settling (assuming a stagnant slurry), the SS seed particles will settle below Y_G of 0.06 and will not settle above this value.

Figure 3 also compares the location of the various simulant tests with the full-scale mixing at three points. The full-scale MJPs have a jet velocity of 18.3 m/s (60 ft/s) and the blue line shows the range of Re_T and Y_G for the 100 micron seed particles at the full-scale velocity. The cohesive simulant testing conducted in this study spanned three different regions on this plot. The 0.3 Pa simulant (MJP operating 30.3 and 37.8 lpm) was in the region where there is no cavern (fluid motion occurred everywhere) and particles will settle within the carrier fluid. For these tests, the batch transfer and mixing behavior was equivalent to water. The 1.6 Pa simulant showed the beginning of cavern formation when the MJP was at 30.3 lpm, which is the slight lower positioned green datum. This test suggests the horizontal line should be at Re_T ~ 30,000. The 1.9 Pa simulant with the MJP at 37.8 lpm showed no cavern (fluid motion everywhere) and is appropriately above the horizontal line. These two tests are in a region where there is effectively no cavern and the seed particles do not settle within the carrier fluid. For both of these tests, the batch transfer results showed more seed particles transferred in comparison to water. The 6.4 Pa simulant with the MJP at 37.8 lpm and 7.0 Pa simulant with the MJP at 30.3 lpm both showed a distinctive cavern and are appropriately below the horizontal line. During periods of testing with these simulants, the MJP was operated at approximately 45.4 lpm to fully mix the tank. At 45.4 lpm, there was essentially no cavern (fluid motion everywhere) and again the horizontal line is appropriately located at 30,000. For these highest yield stress slurries, the region of behavior is to have a cavern and the seed particles that do not settle within the carrier fluid, and this is what was observed. For these tests, the batch transfer results showed even more seed particles transferred in comparison to water.

The overall trend of increasing the slurry yield stress is the total transfer of seed particles always increased with increasing yield stress. What appears to happen with jet mixing of yield stress slurries is that it is more difficult to suspend particles from the tank bottom with increasing yield stress, but the particles stay suspended to a greater degree once lifted from the tank bottom. The combined effect of increasing the yield stress is then an increase in the transfer of seed particles.

The full-scale tank operates at a higher jet velocity, and hence higher jet Reynolds number, and is shown with the blue line above the current test data. The current small-scale test conditions shown in Figure 3 indicate that the small-scale tests include the key regions of full-scale behavior. A number of simple thought evaluations can be made with the current test data in comparison to the behavior that will occur at full-scale velocity. The green arrows show two extrapolations of the current test data to values of Re_T and Y_G that represent full-scale jet velocity. For the green test data, moving to larger Re_T should improve the suspension of seed particles from the tank bottom and also the overall mixing and suspension of particles. Moving to larger Y_G (for example smaller particles) should result in less particle settling and hence better overall mixing and suspension. Both of these simple extrapolations suggest that the mixing behavior at full-scale will be improved. Similar arguments apply to the low- and high-yield stress data pairs. Overall, the current results for batch transfer showing the impact of cohesive particle interactions, which are reflected in a range of yield stress values, are expected to be representative of the impact of cohesive interactions in full-scale tank mixing.

The dimensional analysis indicates that the regions of behavior for full-scale mixing have been adequately represented by the current mixing/transfer demonstrations. Also, this analysis highlights the role of a yield stress (due to cohesive particle interactions) for the four regions of behavior and indicates how the results obtained in this study can be applied to the full-scale mixing behavior of DST waste. It should be noted that the location of the horizontal line for Re_T was determined by the test data for the kaolin slurries and actual waste behavior may be somewhat different. Similarly, the location of the vertical line for Y_G was taken from the literature and actual waste behavior may again be somewhat different.

Figure 4 is a plot of the gravity yield number versus the average SS transferred to the RTs. Only the tests with a simulant that had a yield stress and the water/SS test (Test

1) are included in the plot. The plot suggests as the Y_G for a simulant increases, the average transfer of solids also increased.

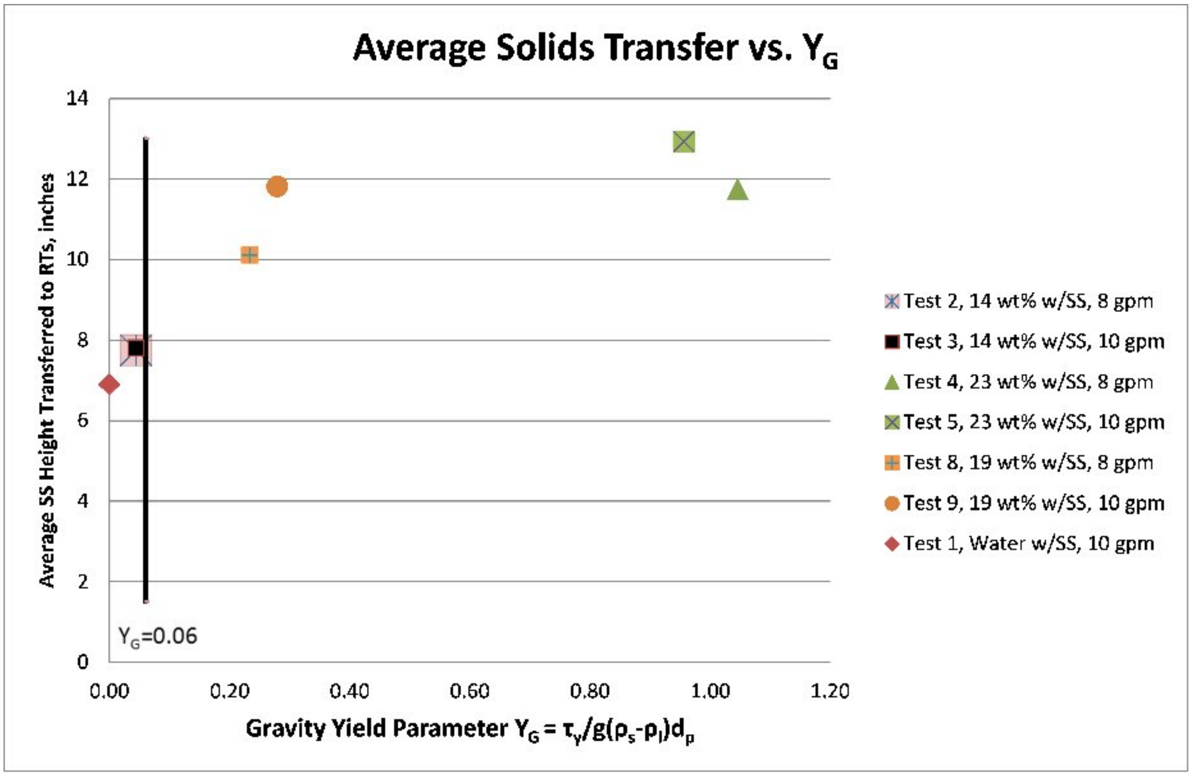

Figure 4: Gravity Yield vs. Average SS Transferred to Receipt Tanks

This finding shows that cohesive particle interactions, which impart a yield stress to the slurry, result in an overall increase in seed particle suspension and transfer, which is an improvement in mixing performance.

CONCLUSION

Testing results show that water always transfers less seed particles, and is conservative when compared to fluids with a higher yield stress and/or higher viscosity at the same mixing/transfer parameters. The impact of non-Newtonian fluid properties depends on the magnitude of the yield stress. A higher yield stress in the carrier fluid resulted in more seed particles being transferred to the RTs. A dimensional analysis highlighting the role of a yield stress (due to cohesive particle interactions) defined four regions of behavior and indicates how the results obtained in this study can be applied to the full-scale mixing behavior of a high level waste tank. The analysis indicates that the regions of behavior for full-scale mixing have been adequately represented by the current small-scale tests.

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