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Mobilization of Cohesive Sludge in Storage Tanks Using Jet Mixers

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Summary

Sludge resides on the floors of many U.S. Department of Energy (DOE) radioactive waste storage tanks. Sludge is

composed of fine-grained particles cohesively bonded together by both colloidal and mechanical forces. Sludge retrieval from these tanks is difficult because access is limited and radiation exposure concerns necessitate remote operation. We are studying the relationship between sludge properties and the mixing system requirements so that a sludge retrieval system can be defensibly designed.

We performed tests in which simulated radioactive sludge was suspended and mixed using submerged, horizontal fluid jets. The fluid jet was generated by a free jet flow agitator (FJFA). Tank diameters used for the tests were 0.45 m, 1.8 m and 5.7 m. Sludge shear strengths ranged from 10 Pa to 2000 Pa.

For most sludge simulants, the shear stress required for mobilization is correlated with the undisturbed sludge strength. In general, the average wall shear stress required to mobilize 80% of the sludge was approximately 5.0% of the measured shear strength. Mixing system performance is predicted by estimating the fraction of the tank floor where the applied shear stress exceeds the sludge's estimated critical shear stress. Computational modeling of the floor's shear stress distribution in our 5.7 m diameter tank test yields sludge mobilization predictions reasonably consistent with our results.

Introduction

The Pacific Northwest National Laboratory (PNNL), Savannah River Site and ITT Flygt Corporation conducted a joint mixer testing program sponsored by the DOE to evaluate the applicability of Flygt mixers to nuclear tank waste retrieval. Testing was carried out in three different tank sizes so that a scaling method could be evaluated and validated and the results could be used to make a full-scale mixer performance prediction [1]. Flygt Submersible Mixers consist of an electrically powered 3-bladed propeller surrounded by a close-fitting shroud. Fig. 1 shows a Flygt mixer. Depending on the size of the tank, different sized or propeller numbers were used. A rapidly spinning propeller creates a turbulent jet with an average exit velocity 3 m/s for a 4 hp mixer.

Fig. 1 ITT Flygt Mixer

This presentation focuses on testing the mobilization of the sludge simulant composed of fine-grained particles cohesively bonded together by both colloidal and mechanical forces. To achieve the right property of the simulant, kaolin clay was used. In some cases bentonite clay was added to increase the fraction of sludge strength due to cohesion rather than friction. Shear strength t_s is the maximum shear stress a material can withstand without rupture. For sludge, this is most readily measured using a shear vane.

The cohesive sludge suspension tests provided the relationship between the average wall stress t_o [2] and the required

stress to induce mobilization (i.e., the critical shear stress t_c). When the shear stress applied to the sludge surface by the turbulent jet exceeds the t_c value of sludge, erosion occurs.

Small Scale Sludge Mobilization Test Phase A

The test was performed in a 0.45 cm diameter Plexiglas tank with the water level inside the tank adjusted to 17.7 cm or 25.7 cm. The water temperature was 15°C. The small scale mixer has a 3-bladed propeller with a 7.8 cm diameter and a pitch of about 5.2 cm (about 12° angle). A load cell was used to measure the axial thrust produced by the small-scale Flygt mixer. The mixer was positioned horizontally, close to the wall and as close as possible to the bottom aimed towards the opposite wall but about 10° to the left of the tank's centerline. For the purpose of data analysis, a subset of the mixer thrust vs. mixer speed data were fitted to the mixer thrust affinity law.

The sludge mobilization test results are shown in Table 1.

Table 1. Small Scale Sludge Mobilization Test Phase A

Test no.	**t_o for 80% Mobilized (Pa)**	**t_o for 95% Mobilized (Pa)**	**t_y (Pa)**	**t_s (Pa)**	**(t_o 80%) / t_s**
1A	4.8	12.2	$7<t_y<50$	$7<t_s<50$	0.1 to 0.7
2A	<9.5	<9.5	» 2.4	» 2.4	<4.0
3A	9.5 to 15	15	100	100	0.095 to 0.15
4A	4.7	£ 7.5	100	100	0.047
5A	50	>50	100	800	0.063
6A	69	>69	150	2000	0.035
7A	<4.7	4.7 to 7.4	10	10	<0.47

notes: τ_o is the average wall shear stress, which equals total mixer thrust divided by wetted area. τ_y is the sludge dynamic yield stress and τ_s is the vane shear strength.

The fraction of sludge mobilized was computed based on a mass-balance calculation and measured slurry density.

There is some uncertainty in the sludge properties for tests no.1A and no.2A. In Tests no.1A and no.2A, the target shear strength and yield stress were both 50 Pa. A 43.5 wt.% kaolin clay slurry was prepared for these tests. Previous testing has shown that this concentration of kaolin has a shear strength and disturbed yield stress of 50 Pa [3].

The sludge strength was likely decreased to some unknown extent. Judging by the thickness of the sludge layer just prior to testing (3 cm), the average weight percent solids throughout the layer is estimated to have been 31.7 wt%. Previous testing has shown that a kaolin slurry with this concentration has a yield stress of about 7 Pa. It is likely,

however, that the fraction of sludge nearest the tank floor had concentration greater than 31.7wt% but less than or equal to 43.5 wt%.

Test no.2A was performed by letting the fully mixed slurry from test no.1A settle to form a layer roughly 3.8 cm thick. The average kaolin concentration in this slurry layer is estimated at 26 wt%. The yield stress of a 26 wt% kaolin slurry is approximately 2.4Pa. Again, there may have been a significant vertical concentration gradient through the layer, so the yield stress of the simulant nearest the floor was probably higher than 2.4 Pa.

The data given in Table 1 are plotted in fig.2. Fig. 2 shows the effect of simulant shear strength on the average wall shear stress required to reach roughly 80% of the sludge mobilized. It appears that the required wall shear stress is roughly 5% of the sludge simulant shear strength. This estimate is very rough, however, because so few data points are present. By comparison, the effect of disturbed simulant yield stress on the average wall shear stress required to mobilize 80% of the sludge, shows that the disturbed simulant yield stress does not provide as good a measure of sludge mobilization resistance as does the undisturbed shear strength. This is consistent with previous mobilization testing from literature [4, 5]. It can be expected that by allowing more time at given mixer speed a larger amount of sludge would be mobilized than was measured. The magnitude of this increase, however, is not known.

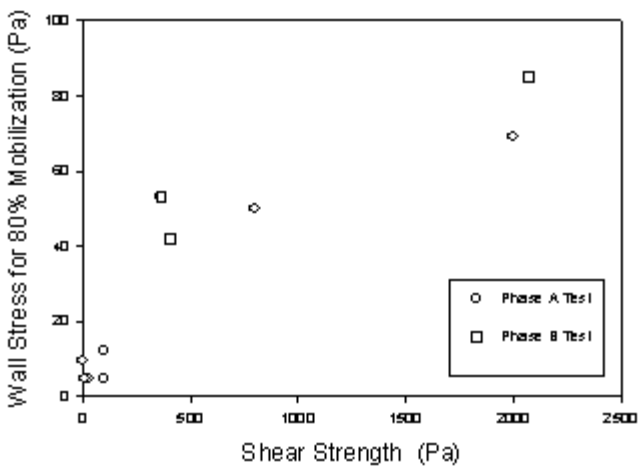

Fig. 2 Effect of Shear Strength on Sludge Mobilization

Sludge Mobilization Test Phase B in Larger Scale

In this case the test was performed in two different tank sizes. The smaller tank was 1.8 m in diameter and larger tank was 5.72 m in diameter. In the smaller 1.8 m diameter tank the measured simulant shear strength was 405± 83 Pa and 2070± 600 Pa. Shear strength measurements were made several days after the test, but the shear strength of the kaolin or kaolin/bentonite based simulant does not change with time provided that water content is maintained [3, 4]. The relatively large uncertainty in the shear strength measurements results primarily from the variations of measurement taken from various locations in the tank.

Test 1B and 2B: In the 1.8 m diameter tank one Flygt mixer (Model 4640) was used. At full load, the mixer motor provides 4 hp at the shaft and generates 810 N of thrust. The mixer propeller-blades are 37 cm in diameter and have a blade angle of 11 degrees. The three blades are mounted inside a jet ring, which directs the flow of liquid through the blades. The mixer is mounted to "a floor mounted mixer stand". In the 1.8 m diameter tank the mixer configuration corresponds to the arrangement in the small scale.

In both cases an 8 cm thick layer of kaolin clay or kaolin with addition of bentonite clay was placed on the tank bottom and covered with water until the liquid level reached 70.6 ± 1 cm. The 405 Pa shear strength simulant was nominally

57% kaolin clay and water. The 2070 Pa shear stress simulant was composed of kaolin clay and bentonite clay. The bentonite clay was added to the mix to increase the fraction of sludge strength due to cohesion rather than friction.

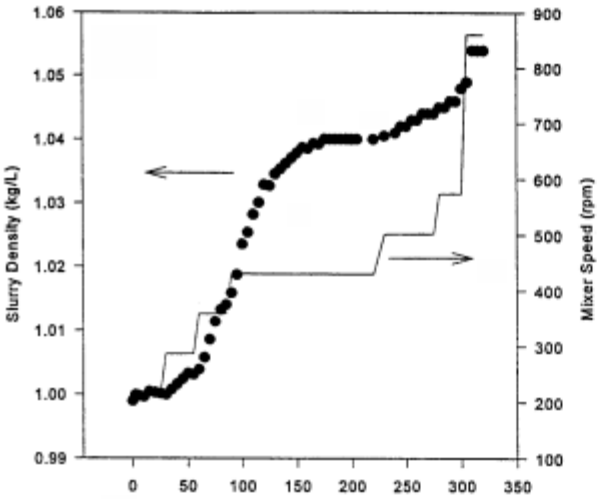

Fig. 3 Slurry Density Data (Test 1B)

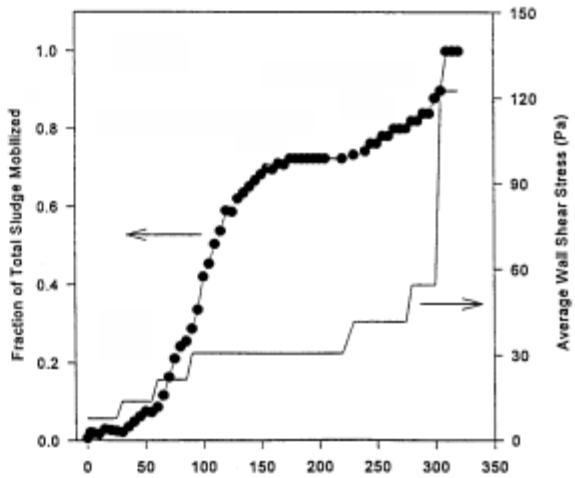

Fig. 4 Fraction Sludge Mobilized and Average Wall Shear Stress (Test 1B)

The mixer speed was gradually increasing while the density was monitored (Krohne Model 2000-300P). The density and mixer speed versus time data are given in figures 3 and 5. The mixer was allowed to run in the each case for an extended period at some speed to ensure that the mobilization of sludge had effectively stopped. In the fig.5 (for 2070 Pa sludge) a disruption in the continuity of the density data can be noticed due to excessive air entrainment in the slurry. Periodically during the test, the samples were withdrawn using a 100.0 mL pycnometer. Agreement between the pycnometer and the Krohne density meter is excellent during most of the test. Only at 860 rpm mixer speed was the Krohne reading systematically biased low due to severe air entertainment. In this case the pycnometer data more accurately reflect the weight percent solids because large air bubbles are allowed to escape before the pycnometer measurement is made.

Figures 4 and 6 give the fraction of sludge mobilized (as computed from the slurry density) and the average wall stress versus time. From this plot, it is estimated that a mixer speed of about 500 ± 40 rpm was needed to mobilize 80% of the 405 Pa shear strength sludge, and about 800 rpm was needed to mobilize 80% of the 2070 Pa shear strength sludge. The average wall stress at this mixer speed is shown in Table 2. This results are similar to the roughly 5% relationship observed in the 0.45 m small tank during Phase A.

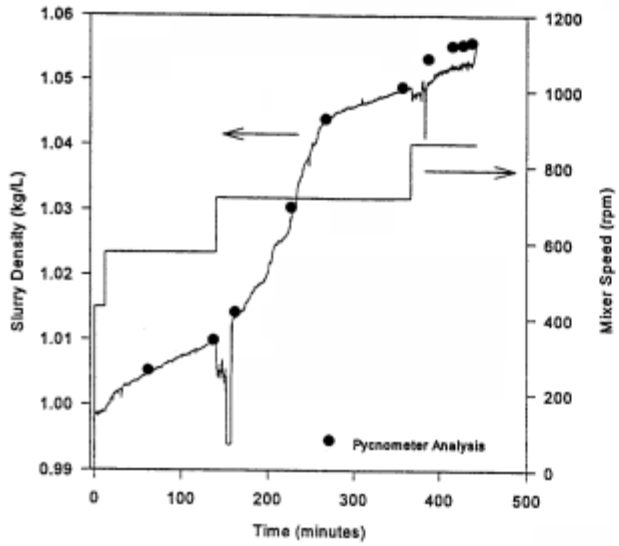

Fig. 5 Slurry Density Data (Test 2B)

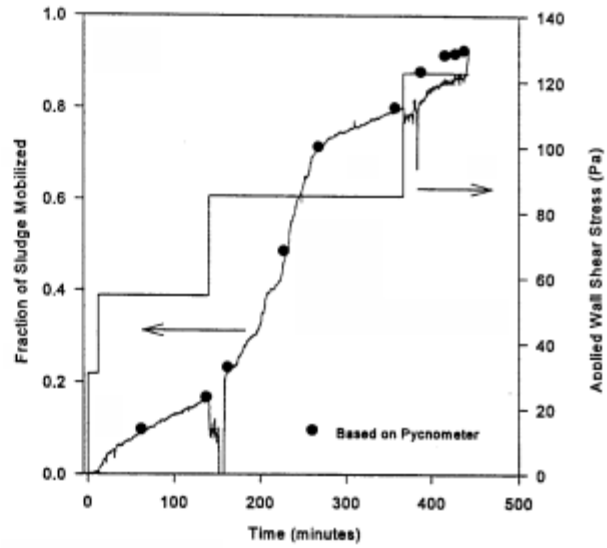

Fig. 6 Fraction Sludge Mobilized Data (Test 2B)

Test 3B: In the 5.72-m diameter tank in Phase B test the three Flygt Model 4640 mixers were used. Their characteristics are as depicted above. The configuration of these three mixers corresponds to the expected deployment orientation in the actual waste tank and is based on riser access limitations. The mixers are positioned with their backs 2.65 m from the tank center and at 60°, 120°, and 300°. The 120° and 300° mixers are directed 30° to the left from the diagonal line between them. The 60° mixer is about 10° away from the center-line.

To evaluate the effects of scale-up on sludge mobilization using Flygt mixers, a kaolin-clay based sludge simulant was placed in the 5.72-m diameter tank. The shear strength and composition of this simulant were nominally the same as that one used for test no.1B in the 1.8-m diameter tank. The actual shear strength and solids concentration were slightly lower than that used in the test no. 1B. The mobilization behavior of kaolin clay in this strength range has shown to not be a strong function of shear strength [4]. The shear strength measured for this sludge was at 363 ± 50 Pa and solids concentration was 56.1 ± 0.8 wt%. When sludge was spread on the bottom, water was added slowly to avoid disturbing the sludge until liquid level reached 2.0 ± 0.02 m. All three mixers were operating at 430 rpm. Little increase in the slurry density was observed over 30 minutes, so the mixer speed was increased to 570 rpm. Again, little increase was observed, so the mixer speed was adjusted to 720 rpm after an additional 25 minutes. Operation at this speed continued until 6 hours had elapsed since the test began. The slurry density was still increasing slowly, but only about 20% of the sludge had been mobilized. The mixers speed was then set to 860 rpm. The mixers speed was maintained for 24 hours and the slurry density stabilized at about 1.009kg/L. This slurry density corresponds to approximately 55% of sludge mobilized. The density and mixer speed data for this test versus time are plotted in fig. 7 The fraction of sludge mobilized and the average wall stress data are provided in fig. 8.

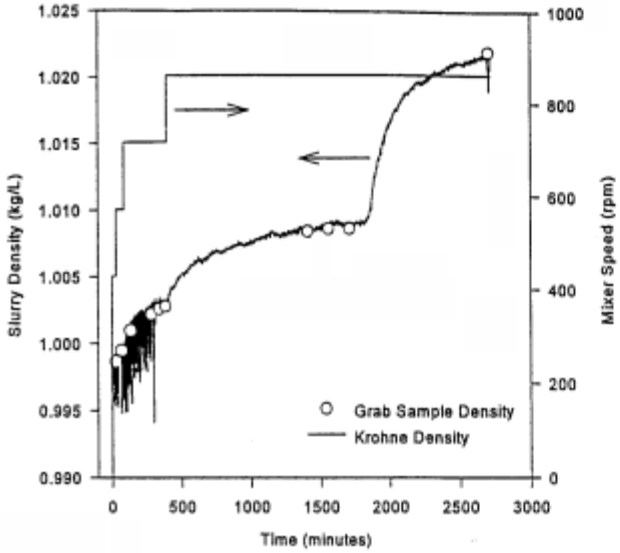

Fig. 7 Slurry Density Data (Test 3B)

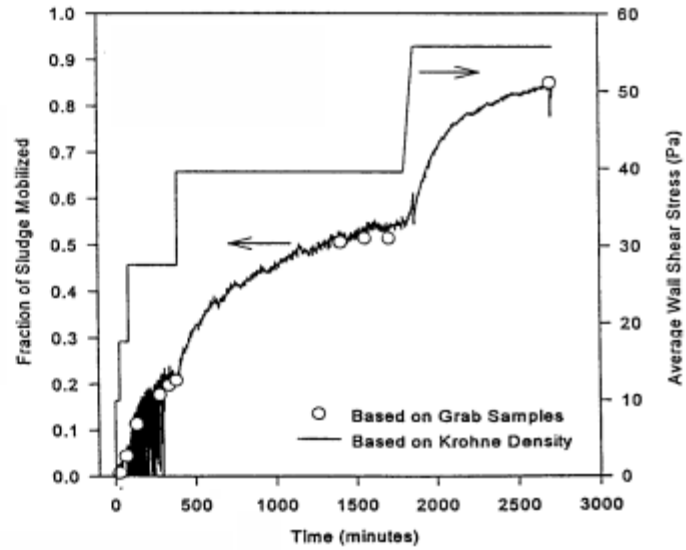

Fig. 8 Slurry Fraction of Sludge Mobilized (Test 3B)

After 24 hours of mixing at 860 rpm, the liquid level was decreased from 2.0 to 1.0 m. This reduction in fluid volume increases the applied shear stress. Full speed mixer operation continued under this new condition for an aditional 15 hours. During this time, the density increased to nearly 1.022 kg/L and the fraction of sludge mobilized reached about 85% (based on the total amount of sludge simulant initially placed in the tank).

With the mixers continuing to operate, the retrieval pump was activated and remaining slurry pumped out. The remaining sludge was collected in the steel drum to determine its volume. It was estimated that 90% of the sludge was mobilized and removed from the tank by weighing the kaolin remaining in the tank. The discrepancy between the 85% value indicated by the density measurements and the 90% value is likely due to a combination of experimental uncertainty and the additional sludge mobilized as the liquid level decreased when the slurry was pumped out of the tank. The average wall shear stress required to result in 80% of the sludge mobilized is estimated to be about 53 Pa. Mixing at the 2.0-m liquid level (40 Pa average stress) resulted in about 55% of the sludge mobilized and mixing at the 1.0-m level (56 Pa average stress) resultes in 85% of the sludge mobilized. Interpolating lineary between these two points gives an estimate of 53 Pa being required to yield 80% of the sludge mobilized.

The shear strength of the sludge simulant used in this test was measured at 363 ± 50 Pa. Assuming an uncertainty in the average wall stress estimate about 10 Pa, the ratio between applied average wall stress and sludge shear strength required to achieve 80% mobilized is 14.6 ± 3.4%. This ratio is somewhat higher than the ratio observed in the 1.8-m tank. All the test results from the phase B are shown in Table 2.

Table 2. Large Scale Sludge Mobilization Test Phase

Test no.	t_o for 80% Mobilized (Pa)	t_s (Pa)	(t_o 80%) / t_s (Pa)
1B	42 ± 7	405 ± 83	0.1 ± 0.03
2B	85	2070 ± 600	0.041 ± 0.012
3B	53 ± 10	363 ± 50	0.146 ± 0.034

Final Remarks

The sludge mobilization process is qualitatively different than the suspension of rapidly settling solids. Therefore, a different analysis approach is used. For our purposes, the sludge is composed of very small, cohesive particles. To mobilize a given piece of sludge away from the sludge interface, the local fluid velocity (or shear stress) must exceed some minimum value for some minimum amount of time. The exact value of the required velocity and time is a function of the sludge properties and to some extent the slurry properties. Once these criteria are met, a particle or group of particles (flake) is removed from the sludge surface thereby exposing the particles underneath to the erosive action of the flowing slurry. Then the process is repeated.

The dislodged pieces of sludge tend to be small, usually millimeter size and smaller. These flakes of sludge are rapidly ground down to particles and clumps of particles with sizes on the order of tens of microns and smaller as the flakes circulate through more strongly mixed regions of the tank (i.e., through the mixer propeller). From there, the particles are slowly settling and only a small amount of agitation is required to maintain them in suspension off the tank floor. Thus, once a piece of sludge is dislodged from the bulk, it effectively no longer presents a difficult challenge from a mixing perspective if sufficient agitation exists in the tank to ensure that the dislodged pieces are broken down into very small, slow settling particles that do not flocculate. For sludge mobilization, the challenging step in the process is dislodging small pieces of the sludge from the bulk of the sludge layer. The subsequent mixing is usually comparatively easy and is ignored in the analysis.

Because maintaining the sludge particles in suspension can be accomplished using comparatively little mixing energy, the effect of decreasing liquid level results in an increase in the average wall shear stress, which is expected to result in a greater degree of sludge mobilization. Sludge mobilization occurs whenever the applied shear stress at the sludge surface exceeds some minimum value. This minimum shear stress for mobilization is called the critical shear stress and is related to the physical properties of the sludge. Previous work with sludge simulants has shown that critical shear stress can be correlated with sludge shear strength. As a *rough* approximation, the critical shear stress is on the order of $1/200^{th}$ of the shear strength [4, 6].

The approach used in the Phase A and B sludge mobilization analyses relates the sludge shear strength to the average wall shear stress (the average shear stress t_o is equal to the total mixer thrust divided by the wetted surface area of the tank) required to achieve 80% of the sludge mobilized. The 80% level was arbitrarily chosen to represent an acceptable degree of mobilization. This same criterion was applied to all the tests for a more direct comparison. This approach does not consider the changes in shear stress distribution on the sludge surface with changes in mixer speed, number of mixers, or the extent of sludge mobilized.

A more rigorous analysis of the Phase A and B sludge mobilization test data required that the shear stress distribution be determined for each of the tests and for the planned full-scale application. In general, such an effort was beyond the scope of the present work. However, in one case only (for the test 3B) the floor's shear stress distribution from computational modeling was done [7]. From the results on Figs. 9 and 10 can be seen that for two different water levels (1 m and 2 m) sludge mobilization predictions are reasonably consistent with test results.

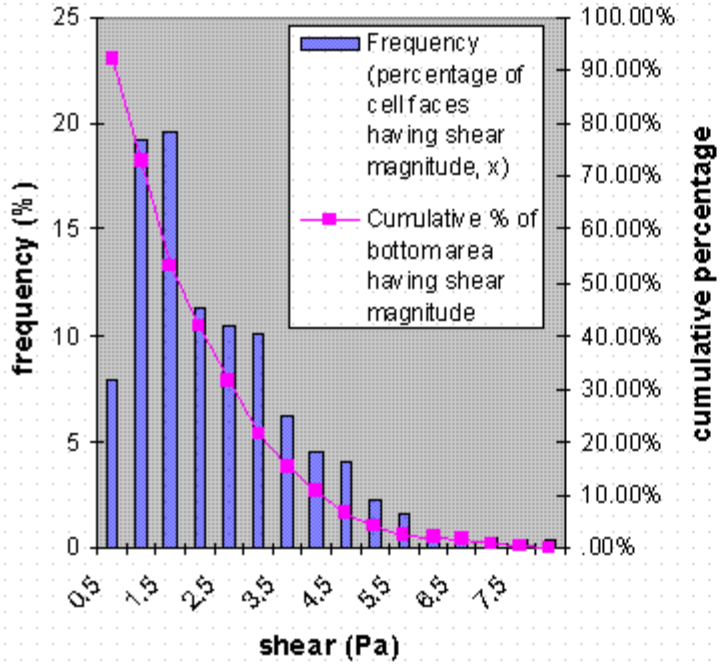

Fig. 9 Bottom Shear Stress in the Tank with 3 Mixers and 2 m Liquid Level

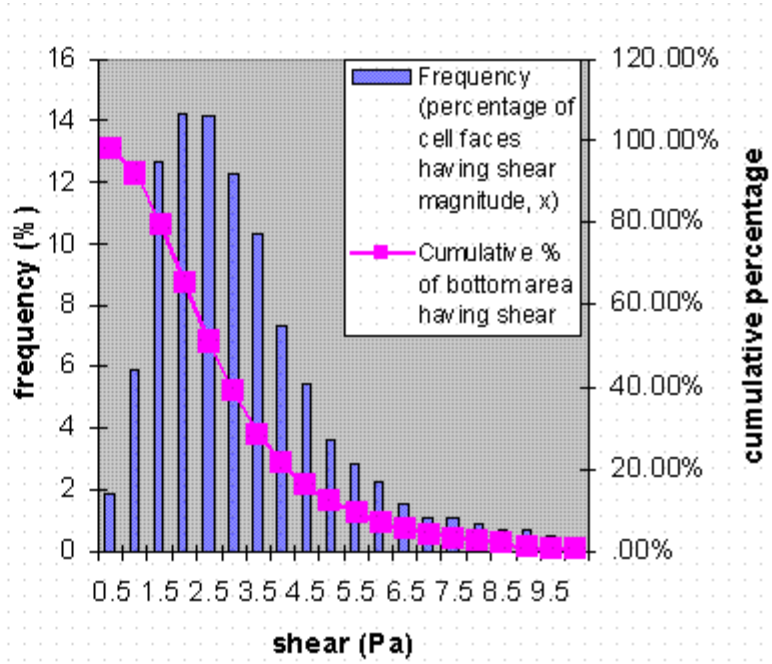

Fig. 10 Bottom Shear Stress in the Tank with 3 Mixers and 1 m Liquid Level

Tests using Flygt mixers to mobilize and mix cohesive sludge simulants were performed in both Phase A and B tests. Phase A testing indicated that the average wall stress t_o required to achieve 80% of the sludge mobilized was 5 ± 1.5% of the sludge shear strength when the strength was greater than 100Pa. The findings of the Phase B tests are consistent with those of Phase A (all results are in fig. 2). The no. 2B test used kaolin/bentonite/water sludge simulant with shear strength of 2070 ± 600 Pa. The t_o required to achieve 80% mobilization was found to be 4.1 ± 1.2% of the shear strength. This result is consistent with no.6A test in small tank in which kaolin/plaster sludge simulant with a shear strength estimated to be 2000 Pa required a t_o of 3.5% of the sludge strength.

Phase B Tests no. 1B and 3B used kaolin/water sludge simulant with shear strength in the 400 Pa range (test 1B was 405 ± 83 Pa and test.3B was 363 ± 50 Pa). The average wall shear stress required to reach 80% mobilization in test 1B was 42 ± 7 Pa. An estimate of 53 Pa in test 3B was generated based on a linear interpolation between these two points, but the relationship is probably not linear. Thus, in the test 1B, the average wall stress required to achieve 80% mobilization was 10 ± 3% of the sludge strength. In the test 3B, the required stress was estimated at 14.6 ± 3.4% of the sludge strength.

A more accurate and complete understanding of mixer sludge mobilization process can likely be attained by considering the shear stress distribution within the tanks used for testing and full scale tanks. In the meantime, a rough estimate of the total mixer thrust required to achieve 80% sludge mobilization is given by multiplying the sludge shear strength by 0.1 ± 0.05.

References

1. Powell M.R., Farmer J.R, Gladki H., Hatchell B.K., Johnson M.A, Porier M.R., Rodwell P.O., Evaluation of Flygt Mixers for Application in Savannah River Site Tank (Summary of Test results from Phase A, B, and C Testing), Pacific Northwest National Laboratory, Richland, Washington, PNNL-12168, 1999.
2. Gladki H. Power Dissipation, Thrust Force and Average Shear Stress in the Mixing Tank with a Free Jet Agitator, Industrial Mixing Fundamentals, AIChE, New York, Vol. 91, p. 146, 1995.
3. Powell M.R., Golcar G.R., Geeting J.G.H., Retrieval Process Development and Enhancements Waste Simulant Compositions and Defensibility. PNNL-11685, Pacific Northwest National Lab.,Richland, Washington, 1997.

4. Powell M.R., Gates C.M., Hymas C.R., Sprecher M.A., Morter N.J.,Scale Sludge Mobilization Testing, PNNL-10582, Richland Washigton, 1995.
5. Graf W.H., Hydraulics of Sediment Transport, McGraw-Hill, New York, 1971
6. Nearing M.A., Parker S.C.,Bradford J.M.,Elliot W.J., Tensile Strength of Thirty-Three Saturated Repacked Soils, Soil Sci. Am. J. 55:1546-1551, 1991.
7. Saunders S., CFD as a Mixing Application Tool, Scientific Impeller, ITT Industry FLYGT, no.5, 1998.