Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

MONITORING AND RESEARCH DEPARTMENT

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EVALUATION OF THE SETTLING CHARACTERISTICS OF NORTH SIDE WATER RECLAMATION PLANT COMBINED SOLIDS AND STICKNEY WATER RECLAMATION PLANT PRELIMINARY SLUDGE

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INTRODUCTION

Eight 80-foot diameter concentration tanks are planned for the Stickney Water Reclamation Plant (WRP) to thicken Stickney Preliminary Sludge (SPS) and North Side Sludge (NSS) as documented in the Stickney Master Plan. NSS is composed of 50% primary sludge and 50% waste activated sludge. The tanks are intended to concentrate sludge to approximately 5% to 6% total solids. Based on the expected annual average flows of the NSS and SPS of 155 tons/day and 355 tons/day, respectively, the loading of the combined Stickney preliminary and North Side sludge to the eight tanks will be approximately 25.4 lb/ft^2-day per tank. The two sludge streams are to be added together into a combined sludge (CS) at a ratio of 1:7 for NSS and SPS. Each tank has a total volume of 3.96 million gallons and is expected to see an annual average flow of 17.01 million gallons per day (MGD) and a maximum 7-day flow of 271.11 MGD. This equates to an average detention time of 5.6 hours and a minimum detention time of 3.5 hours.

Due to the characteristics of the NSS and transport time to the Stickney WRP, septicity problems which could result in flotation issues once NSS is combined with SPS are of concern. Additionally, as the combined sludge is expected to have a percent total solids concentration (%TS) of approximately 0.6%, there are concerns regarding the ability for the concentration tanks to meet the benchmark level of 5-6%.

OBJECTIVE

The Monitoring and Research Department performed laboratory bench tests to evaluate the settling and thickening effects of the combined mixture of NSS and SPS at a ratio of 1:7, i.e. CS. These tests included the assessment of sidewall effects, water column effects, the effect of settling vessel geometries, the effect of the diameter to height (D:H) ratio for different settling vessels, and the effect of dilute mannich polymer addition.

MATERIALS AND METHODS

This sludge settling study was performed in six phases including: 1) A screening level investigation of SPS, NSS, and CS settling rates in 1-liter graduated cylinders and subsequent sludge concentration (Phase I); 2) A preliminary evaluation of the effect of various settling vessels on CS settling rates and sludge concentration including a 3.2-liter column, 2-liter beaker, and 1-liter Imhoff cone (Phase II); 3) An investigation of CS settling in 1-liter graduated cylinders and subsequent sludge concentration at four separate settling times: 0.5, 1.0, 3.0, and 5.6 hours (Phase III); 4) An investigation of the initial water column height (WCH) effect on CS settling and sludge concentration in four, 2-liter columns at four separate volumes and WCHs of 500 mL and 9.5 cm, 1,000 mL and 20.9 cm, 1,500 mL and 30.4 cm, and 2,000 mL and 44.1 cm, respectively (Phase IV); 5) An investigation of the D:H ratio effects on CS settling and sludge concentration in different vessels at a constant WCH (Phase V); 4) An investigation of the effects of dilute mannich polymer addition on CS settling and sludge concentration in 1-liter columns (Phase VI). The geometries and volumes of the settling vessels used in Phases I through VI are summarized in Table 1.

SPS can be collected from two locations. The North Stickney Preliminary Sludge (NSPS) was collected from Tanks 1 through 10, the South Preliminary Sludge (SSPS) was collected from Tanks 11 through 20, and the NSS was collected from the access port at the Fine Screens Building on 27 separate occasions from May 2, 2008, through May 28, 2009. (Note: Only SSPS was collected on August 13, 2008, and August 18, 2008.) The NSPS and SSPS were combined at a ratio of 1:1 to produce the SPS. The NSS and SPS were then combined at a ratio of 1:7 to produce CS. All sludge streams collected, as well as the composited CS, were analyzed for percent total solids (%TS) in duplicate.

Phase I

Initial screening tests were performed to determine the effect of passive settling on the final concentration of the settled sludge blanket for SPS, NSS, and CS (May 2, 2008, through May 8, 2009). The three sludge samples were added separately to 1-liter graduated cylinders (A1-A10); all columns used were of similar geometry and fill heights. The columns were inverted ten times to ensure complete mixing. Upon mixing, a timer was started. Although the design average detention time for the new facility is 5.6 hours, the sludge samples were allowed to settle for eighteen hours to evaluate septicity and flotation problems. As the sludge settled, a distinct interface between the sludge blanket and supernatant was formed. The changes in the depth of this settling interface (ΔI) were recorded. Phase I tests were performed on four separate days.

Phase II

Settling tests were performed to preliminarily assess the effect of different settling vessel geometries on the final concentration of the settled sludge for CS (August 13, 2008, through

TABLE 1: SETTLING VESSEL GEOMETRIES AND VOLUMES FOR PHASES I-VI

Phase	Vessel ID	Fill Height (cm)	Diameter (cm)	D:H	Volume (mL)
I	A1	37.2	5.9	0.16	1,000
	A2	34.2	6.1	0.18	1,000
	A3	34.8	6.1	0.17	1,000
	A4	32.6	6.3	0.19	1,000
	A5	32.6	6.3	0.19	1,000
	A6	32.6	6.3	0.19	1,000
	A7	37.2	5.9	0.16	1,000
	A8	32.6	6.3	0.19	1,000
	A9	33.7	6.2	0.18	1,000
	A10	33.7	6.2	0.18	1,000
II	B1	50.0	9.0	0.18	3,180
	B2	17.1	12.2	0.71	2,000
	B3	42.9	9.8	0.23	1,000
III	C1	36.6	5.9	0.16	1,000
	C2	34.8	6.1	0.17	1,000
	C3	36.6	5.9	0.16	1,000
	C4	36.6	5.9	0.16	1,000
IV	D1	9.5	8.2	0.87	500
	D2	20.9	7.8	0.37	1,000
	D3	31.4	7.8	0.25	1,500
	D4	44.1	7.6	0.17	2,000
V	E1	36.4	5.9	0.16	1,000
	E2	36.4	8.0	0.22	1,843
	E3	36.4	9.0	0.25	2,312
	E4	36.4	9.9	0.27	2,801
	E5	36.4	20.5	0.56	11,998
	E6	36.4	26.8	0.74	18,900
VI	F0	36.6	5.9	0.16	1,000
	F1	34.2	6.1	0.18	1,000
	F2	36.6	5.9	0.16	1,000
	F3	36.6	5.9	0.16	1,000
	F4	35.4	6.0	0.17	1,000
	F5	35.4	6.0	0.17	1,000

August 18, 2008). Sludge samples were added to a 3.2-liter column with a stir bar to reduce wall effects (B1), a two-liter wide-mouthed beaker to reduce wall effects (B2), and a one-liter Imhoff cone to evaluate the effect of a conical bottom on sludge settling (B3). The CS inside the vessels was completely mixed before the tests commenced. The sludges were allowed to settle for the designed detention time of 5.6 hours, and both settling time and *ΔIs* were recorded. Phase II tests were performed on two separate days.

Phase III

Settling tests were performed to determine the effect of different settling times on the sludge solids concentration of CS (November 5 through November 14, 2008). CS was added to fill four separate 1-liter graduated cylinders (C1, C2, C3, C4, and C5). The columns were inverted ten times to ensure complete mixing. Upon mixing, the tests commenced. The columns underwent different settling times of 0.5 hr (C1), 1.0 hr (C2), 3.0 hr (C3), and 5.6 hr (C4), respectively. The settling time and *ΔIs* were recorded. Phase III tests were performed on four separate days.

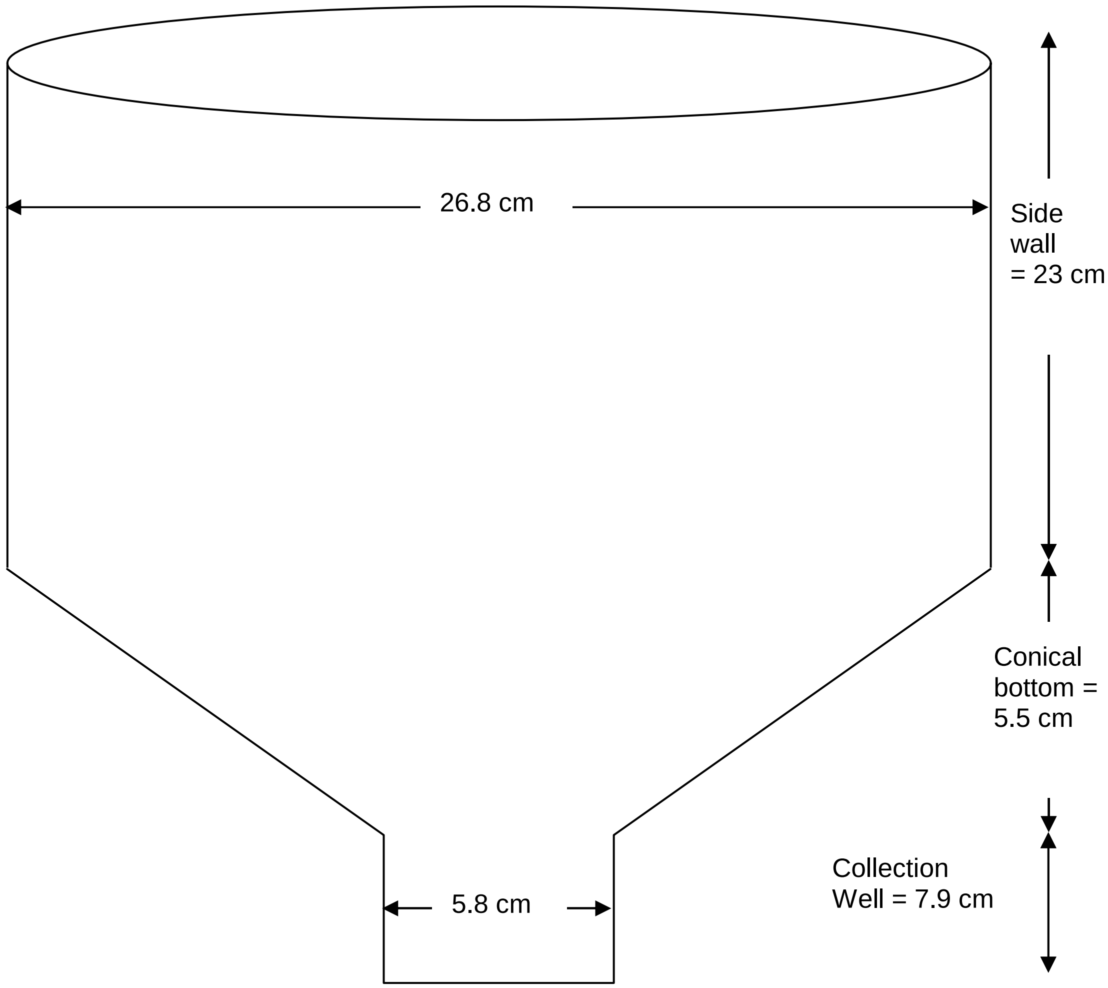
Phase IV

Settling tests were performed to determine the effect of different initial WCHs on the solids concentration of CS (November 20 through December 5, 2008). It was hypothesized that the weight of the water above the solids acts to compress the solids. A higher water column would impart compressive pressure onto the settled sludge thereby producing a more concentrated sludge. To test this hypothesis, four 2-liter graduated cylinders were examined side by side. Different volumes of CS were added to each column: 500 mL (D1), 1,000 mL (D2), 1,500 mL (D3), and 2,000 mL (D4). These volumes resulted in initial WCHs of 9.5 cm, 20.9 cm, 31.4 cm, and 44.1 cm, respectively. The columns were inverted ten times to ensure complete mixing before the tests commenced. The sludge in each column was allowed to settle for 5.6 hours. The *ΔI* was recorded throughout the testing period. Phase IV tests were performed on four separate days.

Phase V

Settling tests were performed to determine the effect D:H ratios and volume on the solids concentration of CS (February 10 through April 21, 2009). Five vessels of varying size were examined: 1-liter (E1), 2-L (E2), 3.2-L (E3), 4-L (E4), and 14-L (E5). CS was added to a height of 36.4 cm in each vessel to minimize any water column effect. Thus, each column had different fill volumes and different D:H ratios. A sixth vessel (E6) was examined at the same fill height to mimic the geometry of the settling tanks planned for the Stickney WRP. However, the vessel was not to scale. Vessel E6 has vertical sidewalls, a conical bottom, and a collection well as depicted in Figure 1; the dimensions are provided in Table 1. In each vessel, the sludge was well mixed immediately prior to testing. The sludge was allowed to settle for 5.6 hours. The *ΔI* was recorded throughout the testing period. Phase V tests were performed on nine separate days.

FIGURE 1: SCHEMATIC OF VESSEL E6 USED IN PHASE V



Phase VI

In Phase VI, settling tests were performed to determine the effect of dilute mannich polymer addition on the concentration of the settled CS (May 7, 2009, through May 28, 2009). The dilute polymer is composed of 40 mL raw mannich polymer in 300 mL deionized water; the mannich polymer was sampled from the Calumet WRP. The dilute polymer was added at six different doses to 1-liter cylinders: 0 mL (F0), 0.1 mL (F1), 0.3 mL (F2), 0.5 mL (F3), 0.7 mL (F4), and 0.9 mL (F5). CS was added to the 1,000 mL mark in each column. The columns were inverted ten times to ensure complete mixing before tests commenced. The sludge was allowed to settle for 5.6 hours. The ΔI was recorded throughout the testing period. Phase VI tests were performed on five separate days.

RESULTS AND DISCUSSION

The results of the solids analysis for tests in each phase are summarized in Table 2. The raw SPS ranged from 0.16 to 3.83%; the raw NSS ranged from 0.59 to 2.59%; the raw CS ranged from 0.25 to 3.60%. The average %TS of raw SPS, NSS, and CS were 0.82%, 1.12%, and 0.83%, respectively.

Phase I

Phase I tests were performed as an initial screening to determine the effect of passive settling on the concentration of the settled sludge for SPS, NSS, and CS. The results of the Phase I settling tests including the settling times and average %TS of the concentrated sludge are summarized in Table 3. The average starting concentrations of tested SPS, NSS, and CS were 2.15%, 1.48%, and 2.06%, respectively. These concentrations were compared to the expected design concentrations identified in "Stickney WRP Revised 98% Preliminary Design Report Volume I of III for Stickney Sludge Thickening Project at Stickney WRP (Contract 96-114-2P)" (Design Report). The Design Report used an annual average of 1.17% for NSS and 0.50% for SPS. At a 1:7 ratio of NSS to SPS, this equates to a CS concentration of 0.58%. Therefore, the %TSs of the SPS, NSS, and CS during Phase I were much higher than the concentrations assumed for design. Additionally, SPS is generally expected to be much less concentrated than NSS. SPS is predominately composed of inorganic solids whereas NSS is a combination of primary and WAS. Because of the high solids concentration observed in SPS, higher organic solids are assumed to have been present.

All tested columns had relatively the same D:H ratio of 0.17-0.18 and fill heights of 34.2 cm to 34.9 cm. Upon test initiation, the tested sludges were allowed to settle for 18 hours. Flotation problems were encountered on the May 2, 2008, and May 7, 2008, for CS. However, only the May 7th test had flotation problems within the design detention time of 5.6 hours. All tests showed an increase in concentration with settling time, as expected. On average, SPS, NSS, and CS concentrated to 3.88%, 2.19%, and 3.56% total solids, respectively. Only the May 8, 2009, tests for SPS and CS exceeded 5% total solids.

Table 3 also summarizes the percent change in ΔI at 0.5 hours and 5.6 hours. Percent change in ΔI ($\%\Delta I$) was calculated as follows,

$$\%\Delta I = \left[1 - \frac{I}{WCH}\right] \cdot 100 \qquad (1)$$

For example, if the WCH is 100 cm, this is considered the starting point of the I, i.e. $I = 100$ cm. When the sludge begins to settle, the interface becomes distinct and steadily moves down the vessel. If the I descends to 40 cm, $I = 40$ cm, and the $\%\Delta I$ equals 60%. This variable $\%\Delta I$ is considered to represent the degree of settling.

The $\%\Delta I$ value for each replicate at 0.5 hours was approximately 2 to 4%. At the design detention time of 5.6 hours, the average $\%\Delta I$ for SPS, NSS, and CS were 19.9%, 10.8%, and

TABLE 2: INITIAL SOLIDS CONCENTRATIONS OF SLUDGE SAMPLED DURING PHASES I-VI

Phase	Date	North SPS	South SPS	SPS	NSS	CS
I	5/2/09	1.33	1.53	1.43	1.32	1.38
	5/6/09	---	2.09	2.09	1.40	2.03
	5/7/09	1.25	1.20	1.25	1.40	1.22
	5/8/09	3.94	3.73	3.83	1.82	3.60
	Average	2.17	2.14	2.15	1.48	2.06
II	8/13/08	---	0.25	0.25	1.17	0.33
	8/18/08	---	0.24	0.24	0.96	0.34
	Average	---	0.24	0.24	1.06	0.34
III	11/5/08	0.15	0.17	0.16	0.91	0.25
	11/7/08	0.30	0.28	0.29	1.41	0.40
	11/12/08	1.62	0.95	1.28	1.04	1.15
	11/14/08	0.47	0.48	0.48	0.78	0.52
	Average	0.63	0.47	0.55	1.04	0.58
IV	11/20/08	0.16	0.26	0.21	0.94	0.29
	11/26/08	0.21	0.28	0.25	0.91	0.29
	12/3/08	0.18	0.22	0.20	0.84	0.27
	12/5/08	0.17	0.20	0.19	0.87	0.26
	Average	0.18	0.24	0.21	0.89	0.28
V	2/10/09	1.26	0.35	0.80	0.81	0.92
	2/13/09	0.50	1.07	0.78	1.07	0.83
	2/17/09	0.44	0.59	0.52	1.06	0.48
	2/24/09	0.43	0.38	0.41	0.93	0.45
	2/26/09	1.03	0.86	0.95	1.06	0.91
	3/3/09	1.46	0.31	0.89	1.00	1.10
	4/16/09	1.18	0.32	0.75	0.96	0.71
	4/21/09	2.31	1.17	1.74	0.59	1.19
	Average	1.08	0.63	0.85	0.94	0.82
VI	5/7/09	0.58	0.26	0.42	2.59	0.66
	5/19/09	0.70	0.85	0.77	1.19	0.82
	5/21/09	0.58	0.56	0.57	1.15	0.64
	5/26/09	0.71	1.16	0.93	1.13	0.96
	5/28/09	0.39	0.40	0.39	0.88	0.46
	Average	0.59	0.65	0.62	1.39	0.71
Maximum		3.94	3.73	3.83	2.59	3.60
Minimum		0.15	0.17	0.16	0.59	0.25
Average		0.89	0.75	0.82	1.12	0.83
Std. Dev.		0.86	0.77	0.78	0.38	0.70

TABLE 3: PHASE I SETTLING TESTS SLUDGE CONCENTRATION RESULTS

Column	A1, A2, A5, A6		A3, A4, A7		A1, A2, A6, A7, A8, A10	
Avg D:H	0.18		0.17		0.18	
Initial WCH (cm)	34.2		34.9		34.6	
Volume (mL)	1,000		1,000		1,000	
Settling time (hr)	18		18		18	
	Stickney Preliminary Sludge		North Side Sludge		Combined Sludge	
Date	Initial %TS	Concentrated %TS*	Initial %TS	Concentrated %TS*	Initial %TS	Concentrated %TS*
5/2/08	1.43	2.76	1.32	2.20	1.38	3.69
5/6/08	2.09	---	1.40	1.40	2.03	3.30
5/7/08	1.23	3.42	1.40	---	1.22	1.95
5/8/08	3.83	5.45	1.82	2.96	3.60	5.28
Maximum	3.83	5.45	1.82	2.96	3.60	5.28
Minimum	1.23	2.76	1.32	1.40	1.22	1.95
Average	2.15	3.88	1.48	2.19	2.06	3.56
Std. Dev.	1.18	1.40	0.23	0.78	1.09	1.37

TABLE 3 (Continued): PHASE I SETTLING TESTS RESULTS SLUDGE CONCENTRATION RESULTS

	%ΔI at 0.5 hours		
Date	Stickney Preliminary Sludge	North Side Sludge	Combined Sludge
5/2/08	4.0	2.0	4.0
5/6/08	---	1.6	2.0
5/7/08	5.0	---**	4.3
5/8/08	3.0	2.0	3.0
Maximum	5.0	2.0	4.3
Minimum	3.0	1.6	2.0
Average	4.0	1.9	3.3
Std. Dev.	1.0	0.2	1.0
	%ΔI at 5.6 hours		
Date	Stickney Preliminary Sludge	North Side Sludge	Combined Sludge
5/2/08	28.0	15.5	21.9
5/6/08	---	10.8	14.0
5/7/08	43.9	---	36.9
5/8/08	19.9	18.3	17.8
Maximum	43.9	18.3	36.9
Minimum	19.9	10.8	14.0
Average	30.6	14.8	22.6
Std. Dev.	12.2	3.8	10.0

*Sludge concentration after 18 hours of settling.
**The NSS sampled on May 6, 2008, was used to make the May 7, 2008, CS.

14.0% respectively. Based on these *%ΔI*-values, the SPS and CS showed better settleability compared to NSS. However, all three sludges experienced extremely inhibited settling.

Based on the Phase I tests, poor settling and minor flotation problems occurred with the CS. Wall effects were assumed to have contributed to the inhibited settling. SPS had higher initial and final concentrations and higher *%ΔI*-values than NSS. As expected, because CS is a combination of both SPS and NSS, the initial and final concentrations and *%ΔI*-values for CS fell between both SPS and NSS. However, after reviewing the total solids content of all three sludges, it is assumed that the sludges tested were not representative of normal plant operations.

Phase II

Phase II settling tests were performed to preliminarily assess the effect of different settling vessels on the final concentration of the settled sludge for CS. The results of the Phase I settling tests including the settling times and average %TS of the concentrated sludge are summarized in Table 4. Based on the initial SPS and NSS concentrations (0.34% and 1.06%, respectively), the sludges tested were more representative of normal plant operations as suggested in the Design Report (0.50% and 1.17%, respectively).

On both August 13, 2008, and August 18, 2008, CS was added to 1) A 3.2-liter column with a rotating stir bar to minimize wall effects (B1); 2) A 2-liter wide-mouthed beaker to minimize wall effects (B2); and 3) A 1-liter Imhoff cone to assess the effects of a conical bottom on sludge concentration (B3). In each vessel, CS was allowed to settle for the design detention time of 5.6 hours.

The average %TS of the concentrated solids for B1, B2, and B3 were 2.56%, 1.48%, and 2.41%, respectively. On average, the vessels with the lowest D:H ratio proved to have the most concentrated sludge. The 2-liter beaker resulted in the lowest settled sludge concentrations, which may be due to relatively shallow water column. Additionally, the conical bottom of the Imhoff cone did not increase the concentration as much as expected and performed similar to the 3.2-liter stir column results. No tests resulted in a final concentration of 5% total solids.

A high degree of settling was observed for each test. On both days, the CS settling exceeded 90% *%ΔI* within the first 30 minutes. Little improvement was observed at the 5.6 hour mark. This high degree of settling is also shown in Figures 2a through 2c which show *I* plotted against the settling time for each settling vessel. For each vessel, all sludges settled rapidly, i.e. no change in sludge blanket thickness or level was observed after 30 minutes settling time. Wall effects seemed to be insignificant.

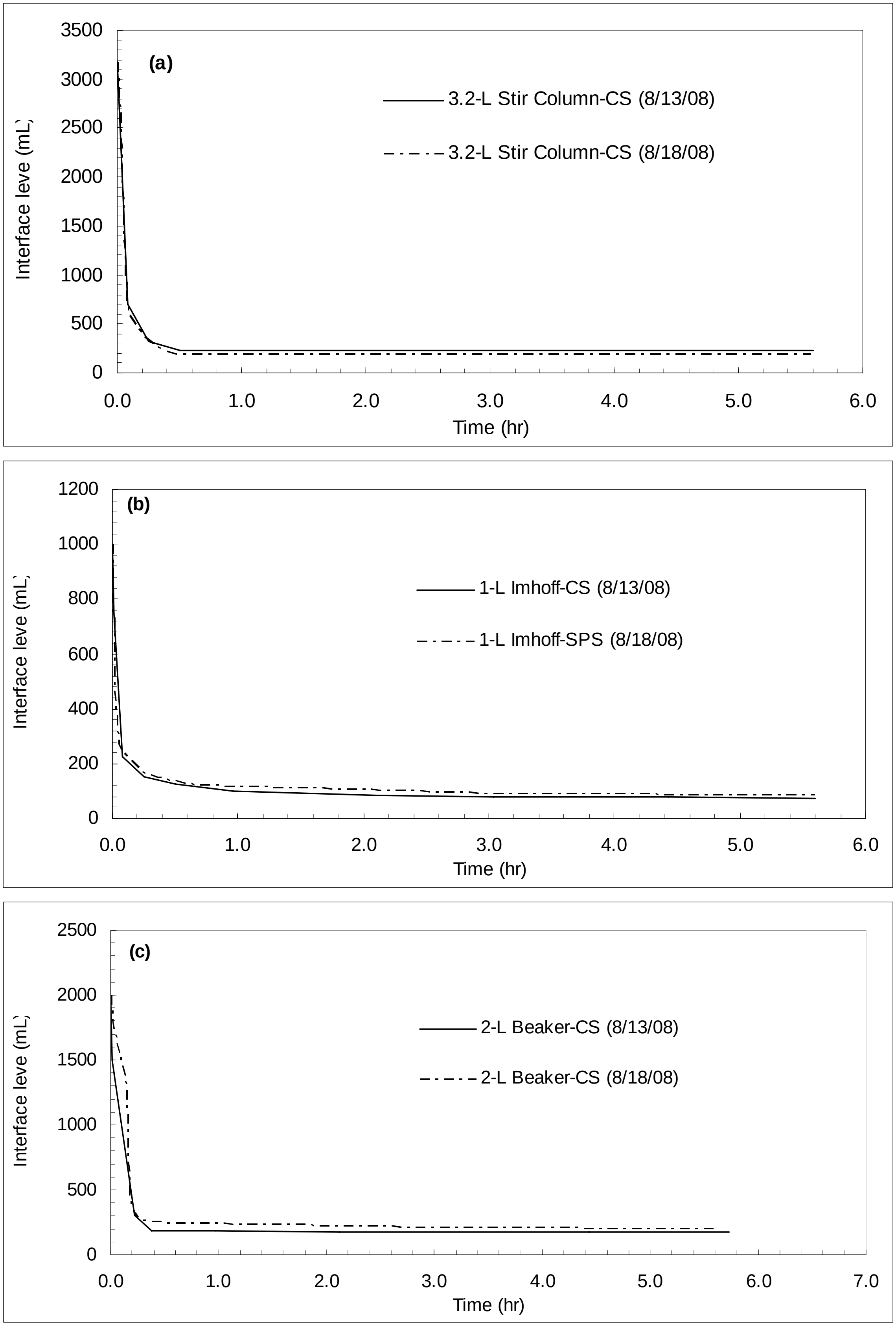
Finally, the percent total solids of the concentrated sludge for each vessel was examined versus the vessel's D:H ratio and initial WCH. In general, as WCH increased, %TS of the settled sludge increased. Likewise, as D:H ratio increased, %TS of the settled sludge decreased. Based on these limited results, it can be assumed that a settling vessel with a high initial WCH and low D:H ratio would result in a higher concentrated sludge blanket than a settling vessel with a low

TABLE 4: PHASE II SETTLING TEST RESULTS FOR COMBINED SLUDGE

Column		B1*	B2**	B3***
D:H		0.18	0.71	0.23
Initial WCH (cm)		50	17.1	42.9
Volume (mL)		3,180	2,000	1,000
Settling time (hr)		5.6	5.6	5.6
Date	Initial %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS
8/13/08	0.33	2.89	1.39	2.14
8/18/08	0.34	2.24	1.56	2.68
Maximum	0.34	2.89	1.56	2.68
Minimum	0.33	2.24	1.39	2.14
Average	0.34	2.56	1.48	2.41
Std. Dev.	0.01	0.46	0.12	0.38
			%ΔI at 0.5 hours	
Date		B1	B2	B3
8/13/08		93.0	90.5	87.5
8/18/08		94.0	87.8	85.5
Maximum		94.0	90.5	87.5
Minimum		93.0	87.8	85.5
Average		93.5	89.1	86.5
Std. Dev.		0.7	1.9	1.4
			%ΔI at 5.6 hours	
Date		B1	B2	B3
8/13/08		93.0	91.5	92.5
8/18/08		94.0	90.0	91.5
Maximum		94.0	91.5	92.5
Minimum		93.0	90.0	91.5
Average		93.5	90.8	92.0
Std. Dev.		0.7	1.1	0.7

*B1 is a 3.2-liter stirred column.
**B2 is a 2-liter beaker.
***B3 is a 1-liter Imhoff cone.

FIGURE 2: PHASE II PLOT OF SLUDGE-WATER INTERFACE LEVEL VERSUS TIME FOR THE (a) 3.2-LITER STIR COLUMN; (b) TWO-LITER BEAKER; AND (c) ONE-L IMHOFF CONE



initial WCH and high D:H ratio. The indication is that the column height may have a greater influence on the settled sludge concentration than the D:H ratio.

Phase III

The results of the Phase III settling tests including the settling times and average %TS of the concentrated sludge are summarized in Table 5. All columns had the same D:H ratio of 0.16. As settling time increased, the %TS of the concentrated sludge increased. Figure 3 shows the settling time plotted versus %TS of the concentrated sludge with a linear equation fit to the results (r^2=0.8415). Using this equation, the settling time to achieve 5% total solids in a 1-liter column would be 22.4 hours. This predicted settling time is almost 3.5 times that of the design detention time. However, a straight-line trend would not be expected with longer settling times because limited increases in %TS would occur with increasing time.

Table 5 also provides *%ΔI* at 0.5 hours and 5.6 hours. Except for November 12, 2009, every test indicated that most of the settling occurred within the first 30 minutes, i.e. *%ΔI* ≥ 70%. Based on these results using the 1-L columns, wall effects are considered insignificant.

The highest concentrated sludge was observed on November 12, 2008, in all four vessels, e.g. 4.76% at 5.6 hours for Column D4. It is assumed that these results were due to the relatively high initial raw concentrations of the CS (1.15%).

Phase IV

The results of the Phase IV settling tests including the settling volumes and average %TS of the concentrated sludge are summarized in Table 6. As expected, the %TS of the sludge increased with increasing initial WCHs. Additionally, the %TS of the concentrated sludge decreased with increasing D:H ratios. Figures 4a and 4b show initial WCHs and D:H ratios, respectively, plotted versus the average %TS of the settled sludge. Fitting a logarithmic equation (r^2=0.9039) to Figure 4a, the projected WCH of the designed concentration tanks (23 feet) would result in 3.98% total solids in the concentrated sludge. However, fitting a logarithmic equation (r^2=0.8984) to Figure 4b, the projected D:H ratio of the concentration tanks (3.48) would result in a solids concentration of 0.01%. Based on the results of this study and the corroborating the results of Phase II, it would seem that increasing the initial WCH and minimizing the D:H ratio of the settling vessel would lead to a higher concentration of solids in the settled blanket.

Table 6 also provides *%ΔI* at 0.5 hours and 5.6 hours. Much like the Phase II and III results, every test indicated that the majority of settling was completed within the first 30 minutes of testing, i.e. *%ΔI* ≥ 70%.

TABLE 5: PHASE III SETTLING TESTS RESULTS FOR COMBINED SLUDGE

Column		C1	C2	C3	C4
D:H		0.16	0.17	0.16	0.16
Initial WCH (cm)		36.6	34.8	36.6	36.6
Volume (mL)		1,000	1,000	1,000	1,000
Settling Time (hr)		0.5	1.0	3.0	5.6
Date	Initial %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS
11/5/08	0.25	1.61	1.60	1.52	1.44
11/7/08	0.40	2.17	2.45	0.86	2.47
11/12/08	1.15	2.69	3.30	4.44	4.76
11/14/08	0.52	1.69	2.11	2.55	2.69
Maximum	1.15	2.69	3.30	4.44	4.76
Minimum	0.25	1.61	1.60	0.86	1.44
Average	0.58	2.04	2.36	2.34	2.84
Std. Dev.	0.40	0.50	0.71	1.56	1.39
		%ΔI at 0.5 hours			
Date		C1	C2	C3	C4
11/5/08		90.0	90.0	90.0	93.0
11/7/08		85.0	85.0	85.0	86.0
11/12/08		36.0	44.0	45.5	45.5
11/14/08		66.0	68.0	66.0	67.0
Maximum		90.0	90.0	90.0	93.0
Minimum		36.0	44.0	45.5	45.5
Average		69.3	71.8	71.6	72.9
Std. Dev.		24.5	20.8	20.3	21.3
		%ΔI at 5.6 hours			
Date		C1	C2	C3	C4
11/5/08		NA	NA	NA	93.0
11/7/08		NA	NA	NA	89.0
11/12/08		NA	NA	NA	72.5
11/14/08		NA	NA	NA	81.5
Maximum		NA	NA	NA	93.0
Minimum		NA	NA	NA	72.5
Average		NA	NA	NA	84.0
Std. Dev.		NA	NA	NA	9.0

FIGURE 3: PLOT OF PHASE III SETTLING TIME VERSUS AVERAGE PERCENT TOTAL SOLIDS OF CONCENTRATED SLUDGE

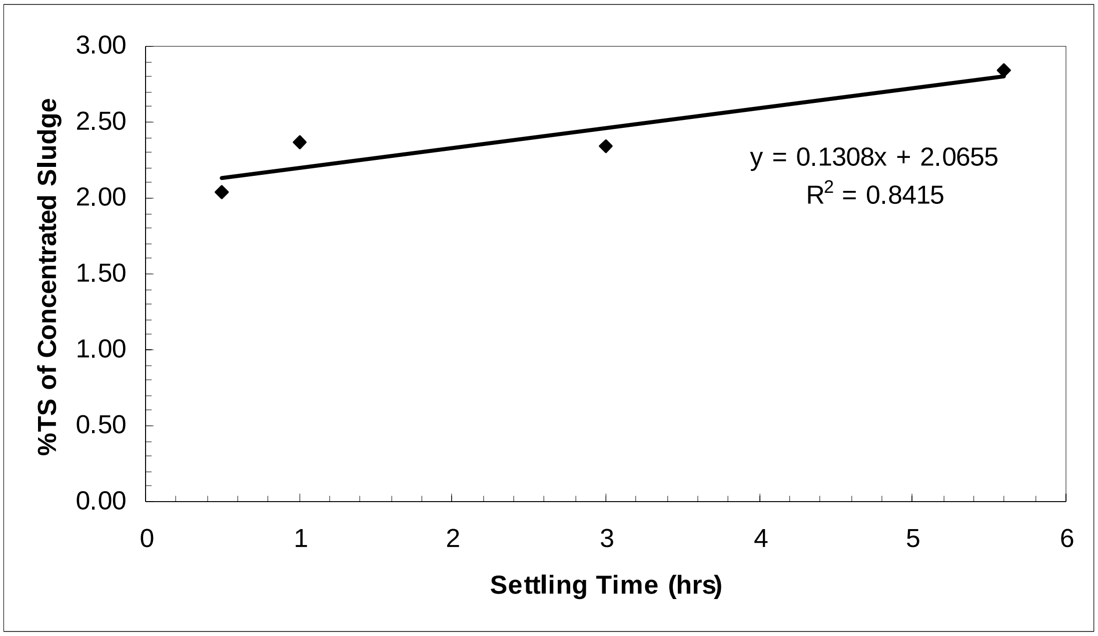


TABLE 6: PHASE IV SETTLING TESTS RESULTS FOR COMBINED SLUDGE

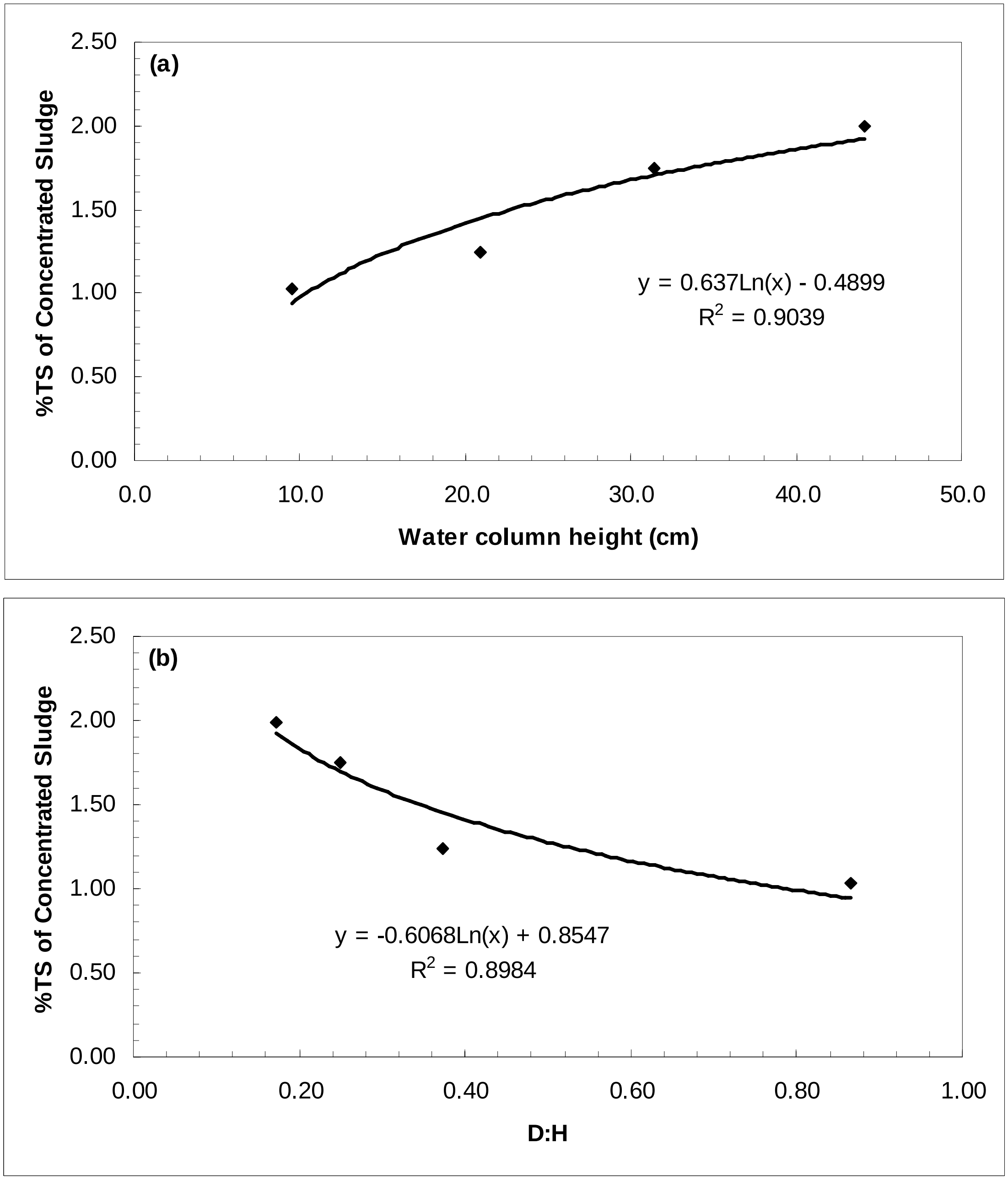
Column*		D1	D2	D3	D4
D:H		0.87	0.37	0.25	0.17
Initial WCH (cm)		9.5	20.9	31.4	44.1
Volume (mL)		500	1,000	1,500	2,000
Settling Time (hr)		5.6	5.6	5.6	5.6
Date	Initial %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS
11/20/08	0.29	0.73	1.22	1.96	2.01
11/26/08	0.29	1.10	1.13	1.83	2.18
12/3/08	0.27	1.28	1.28	1.30	1.92
12/5/08	0.26	1.02	1.34	1.91	1.86
Maximum	0.29	1.28	1.34	1.96	2.18
Minimum	0.26	0.73	1.13	1.30	1.86
Average	0.28	1.03	1.24	1.75	1.99
Std. Dev.	0.01	0.23	0.09	0.31	0.14

	%*ΔI* at 0.5 hours			
Date	D1	D2	D3	D4
11/20/08	84.00	81.00	80.67	79.00
11/26/08	80.00	81.00	79.33	75.00
12/3/08	85.00	88.50	88.00	87.75
12/5/08	86.00	85.00	86.67	86.00
Maximum	86.00	88.50	88.00	87.75
Minimum	80.00	81.00	79.33	75.00
Average	83.75	83.88	83.67	81.94
Std. Dev.	2.63	3.61	4.30	5.97

	%*ΔI* at 5.6 hours			
Date	D1	D2	D3	D4
11/20/08	84.00	87.50	89.00	89.50
11/26/08	84.00	86.00	88.00	89.50
12/3/08	86.00	90.00	89.00	91.25
12/5/08	88.00	90.00	90.67	91.50
Maximum	88.00	90.00	90.67	91.50
Minimum	84.00	86.00	88.00	89.50
Average	85.50	88.38	89.17	90.44
Std. Dev.	1.91	1.97	1.11	1.09

*All columns were 2-liter graduated cylinders.

FIGURE 4: PLOT OF PHASE IV a) WATER COLUMN HEIGHT AND b) DIAMETER TO HEIGHT RATIO VERSUS AVERAGE PERCENT TOTAL SOLIDS OF CONCENTRATED SLUDGE AT CONSTANT DIAMETER



Phase V

The %TS results of Phase V settling tests are provided in Table 7. In these tests, the initial WCH was constant for all tests. However, each vessel used in the tests had a different diameter and therefore a different D:H ratio and test volume (Table 1). It should be noted that the configuration of vessel E6 is similar to the design settling tanks.

On average in Phase V, the vessels with the higher D:H ratios achieved the highest %TS in the settled sludge. It is assumed that the lower concentrated solids observed at higher D:H ratios in Phase IV were due to the shallow water and the subsequent lower compressive forces on the sludge. In Phase V, D:H ratios increases as test volumes increased. Figures 5a and 5b show the D:H ratios and volumes, respectively, plotted versus the average %TS of the settled sludge. Fitting a logarithmic equation (r^2=0.5576) to Figure 5a, the projected D:H ratio of the designed concentration tanks (3.48) would result in 3.68% total solids in the concentrated sludge. Fitting a logarithmic equation (r^2=0.683) to Figure 5b, the projected design volume of the concentration tanks (565,771 gallons or 2.14 x 10^6 liters) would result in a solids concentration of 6.49%, which is even better than design benchmark. However, the opposite trend was observed with regards to D:H ratios when compared to the Phase II and IV results; in Phase II and IV, lower %TS were observed relative to higher D:H ratios.

Table 7 also provides *%ΔI* at 0.5 hours and 5.6 hours. Unlike results from Phases II, III and IV, sludge did not settle as rapidly in Phase V. Taking the average of all six columns (E1-E6), the *%ΔI* was 46.7% in the first 30 minutes and 70.8% at the design time of 5.6 hours. In Phases III and IV, the *%ΔI* was 77.3% and 87.5% at 0.5 hours and 5.6 hours, respectively. Additionally, of the columns with similar geometries (E1–E5), it is observed that the increasing diameter led to increased settling within the first 30 minutes; this may be an indication of slight wall effects. However, this trend was not observed at 5.6 hours. Also, the pilot settling vessel (E-6) had the lowest *%ΔI*.

Phase VI

The Phase VI %TS results and respective polymer treatments are provided in Table 8. Figure 6 shows the tests with polymer addition plotted versus the average %TS of the settled solids. Based on the results, a dose of 0.3 mL of the dilute polymer per 1,000 mL of CS would only slightly increase the %TS approximately 0.22% more than without polymer treatment. The dilute mannich polymer addition still does not provide the 5–6% solids benchmark.

Table 8 also provides *%ΔI* at 0.5 hours and 5.6 hours. Mannich polymer addition did not seem to increase settling velocity. The *%ΔI* at 30 minutes ranged from 58.5%–62.5% at 30 minutes and 77.7%–81.4% at 5.6 hours. The mannich polymer does not appear to be the appropriate polymer to enhance the primary settling.

TABLE 7: PHASE V SETTLING TESTS RESULTS FOR COMBINED SLUDGE

Column		E1	E2	E3	E4	E5	E6
D:H		0.16	0.22	0.25	0.27	0.56	0.74
Initial WCH (cm)		36.4	36.4	36.4	36.4	36.4	36.4
Volume (mL)		1,000	1,843	2,312	2,801	11,998	18,900
Settling time (hr)		5.6	5.6	5.6	5.6	5.6	5.6
		%TS of Concentrated Sludge					
Date	Initial %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS
2/10/09	0.92	2.25	2.90	2.43	3.44	2.26	3.85
2/13/09	0.83	2.08	2.28	2.67	2.48	2.89	2.94
2/17/09	0.48	1.99	2.28	2.56	2.64	2.74	2.75
2/24/09	0.45	2.26	2.26	2.22	2.48	2.69	2.64
2/26/09	0.91	2.21	2.38	2.97	2.89	3.28	2.74
3/3/09	1.10	3.02	3.34	3.87	3.52	2.47	3.19
4/16/09	0.71	2.47	2.55	2.82	2.76	3.03	2.78
4/21/09	1.19	3.82	4.49	4.76	4.61	5.11	4.30
Maximum	1.19	3.82	4.49	4.76	4.61	5.11	4.30
Minimum	0.45	1.99	2.26	2.22	2.48	2.26	2.64
Average	0.82	2.51	2.81	3.04	3.10	3.06	3.15
Std. Dev.	0.27	0.62	0.78	0.85	0.73	0.89	0.61

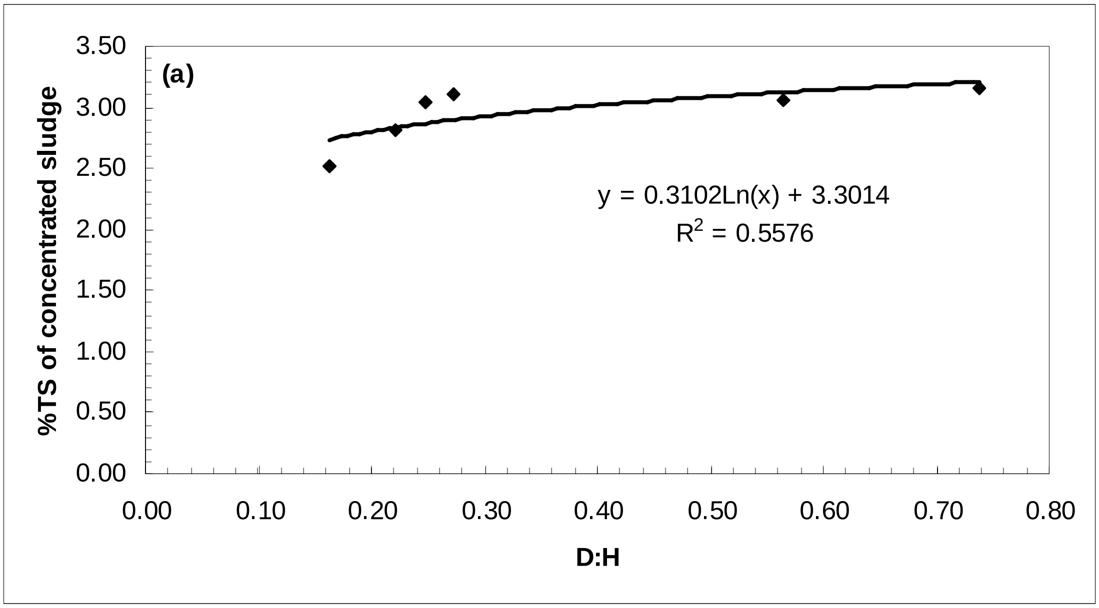
TABLE 7 (Continued): PHASE V SETTLING TESTS RESULTS FOR COMBINED SLUDGE

	%ΔI at 0.5 hours					
Date	E1	E2	E3	E4	E5	E6
2/10/09	78.00	76.15	77.53	67.86	76.62	50.48
2/13/09	23.00	50.41	52.05	44.46	49.93	43.60
2/17/09	67.00	67.21	66.58	66.25	64.24	50.89
2/24/09	72.00	72.09	71.23	71.79	69.74	51.86
2/26/09	12.50	24.12	24.66	14.29	29.44	26.13
3/3/09	28.00	50.14	50.41	57.14	49.66	43.60
4/16/09	13.00	25.75	26.30	21.07	32.32	33.15
4/21/09	13.00	31.71	36.16	33.93	46.35	36.73

	%ΔI at 0.5 hours					
Date	E1	E2	E3	E4	E5	E6
Maximum	78.00	76.15	77.53	71.79	76.62	51.86
Minimum	12.50	24.12	24.66	14.29	29.44	26.13
Average	38.31	49.70	50.62	47.10	52.29	42.06
Std. Dev.	28.84	20.91	20.28	22.18	16.94	9.34

	%ΔI at 5.6 hours					
Date	E1	E2	E3	E4	E5	E6
2/10/09	83.00	83.47	84.38	81.25	84.32	57.36
2/13/09	55.00	65.31	67.67	71.43	69.74	50.48
2/17/09	81.00	81.57	83.56	82.50	83.49	61.49
2/24/09	82.00	83.20	84.38	82.68	84.32	60.11
2/26/09	61.00	72.90	68.49	64.29	66.99	50.48
3/3/09	65.00	71.27	72.05	76.79	72.49	55.98
4/16/09	66.00	69.65	68.49	69.64	68.36	50.48
4/21/09	76.50	68.56	69.59	70.36	68.91	49.66
Maximum	83.00	83.47	84.38	82.68	84.32	61.49
Minimum	55.00	65.31	67.67	64.29	66.99	49.66
Average	71.19	74.49	74.83	74.87	74.83	54.50
Std. Dev.	10.77	7.19	7.80	6.92	7.79	4.82

FIGURE 5: PLOT OF PHASE V a) DIAMETER TO HEIGHT RATIO AND b) TESTED VOLUME VERSUS AVERAGE PERCENT TOTAL SOLIDS OF CONCENTRATED SLUDGE AT CONSTANT WATER COLUMN HEIGHT



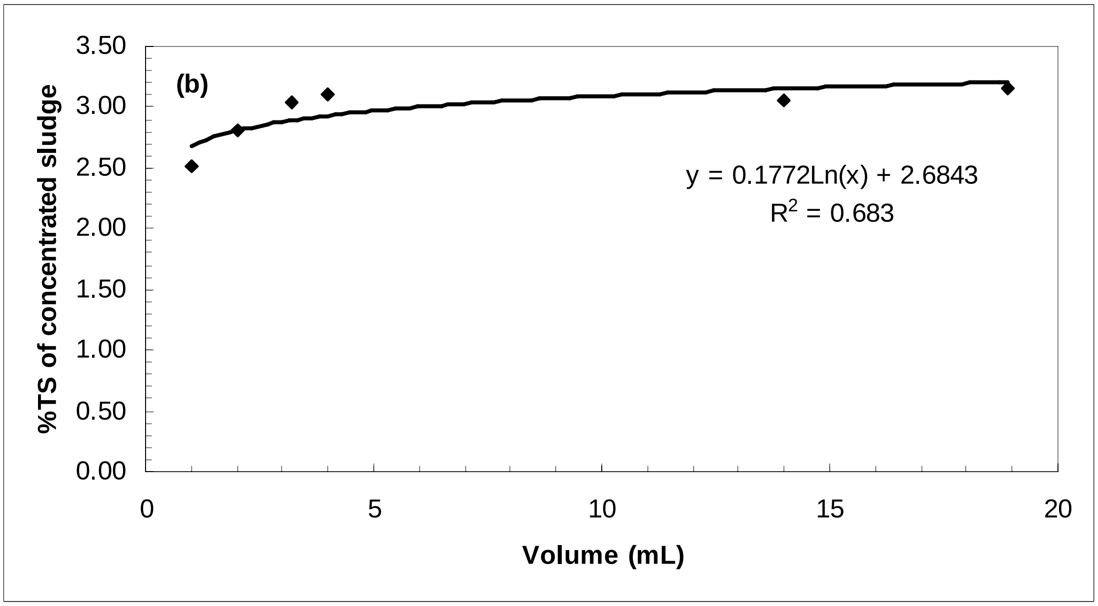


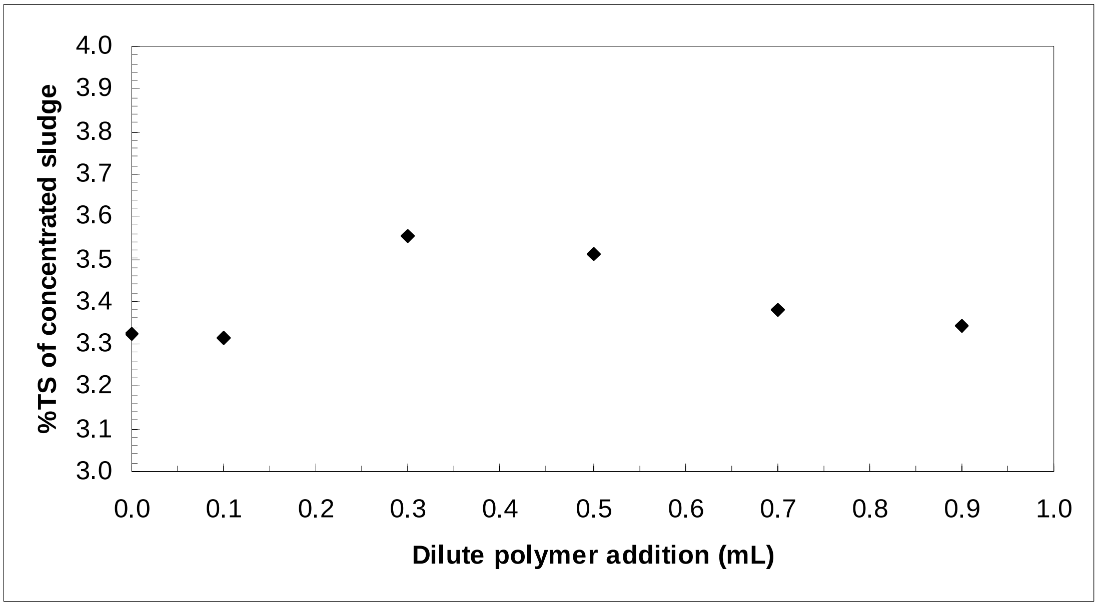
TABLE 8: PHASE VI SETTLING TEST RESULTS

Column		F1	F2	F3	F4	F5	F6
D:H		0.16	0.18	0.16	0.16	0.17	0.17
Initial WCH (cm)		36.6	34.2	36.6	36.6	35.4	35.4
Volume (mL)		1,000	1,000	1,000	1,000	1,000	1,000
Settling Time (hr)		5.6	5.6	5.6	5.6	5.6	5.6
Polymer Dose (mL)		0	0.1	0.3	0.5	0.7	0.9
Date	Initial %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS	Concentrated %TS
5/7/09	0.66	2.77	2.88	3.72	3.83	3.36	3.41
5/19/09	0.82	3.61	3.58	3.49	3.27	3.28	3.12
5/21/09	0.64	3.62	3.32	3.58	3.18	3.35	3.57
5/26/09	0.96	3.62	3.76	3.80	3.93	3.75	3.70
5/28/09	0.46	3.00	3.03	3.18	3.36	3.17	2.92
Maximum	0.96	3.62	3.76	3.80	3.93	3.75	3.70
Minimum	0.46	2.77	2.88	3.18	3.18	3.17	2.92
Average	0.71	3.33	3.31	3.55	3.51	3.38	3.34
Std. Dev.	0.19	0.41	0.37	0.24	0.34	0.22	0.32

TABLE 8 (Continued): PHASE VI SETTLING TEST RESULTS

	%ΔI at 0.5 hr					
Date	F1	F2	F3	F4	F5	F6
5/7/09	77.50	75.50	74.50	75.50	74.50	73.50
5/19/09	26.00	35.00	36.00	52.00	51.00	52.50
5/21/09	74.00	74.00	73.00	71.00	72.00	72.00
5/26/09	33.00	34.00	34.50	32.00	32.50	34.50
5/28/09	82.00	81.00	81.00	81.00	79.50	80.00
Maximum	82.00	81.00	81.00	81.00	79.50	80.00
Minimum	26.00	34.00	34.50	32.00	32.50	34.50
Average	58.50	59.90	59.80	62.30	61.90	62.50
Std. Dev.	26.74	23.34	22.62	20.15	19.71	18.72
	%ΔI at 5.6 hr					
Date	F1	F2	F3	F4	F5	F6
5/7/09	86.00	84.50	82.50	81.50	82.50	81.50
5/19/09	75.50	76.50	74.00	73.00	72.00	71.50
5/21/09	84.00	83.00	81.50	82.00	80.50	80.00
5/26/09	74.50	73.50	73.50	72.50	73.00	72.00
5/28/09	87.00	85.00	85.00	84.50	84.00	83.50
Maximum	87.00	85.00	85.00	84.50	84.00	83.50
Minimum	74.50	73.50	73.50	72.50	72.00	71.50
Average	81.40	80.50	79.30	78.70	78.40	77.70
Std. Dev.	5.95	5.18	5.23	5.55	5.54	5.57

FIGURE 6: PLOT OF PHASE IV POLYMER ADDITION VERSUS AVERAGE PERCENT TOTAL SOLIDS OF CONCENTRATED SLUDGE



SUMMARY AND CONCLUSIONS

A settling and thickening evaluation was performed on a 1:7 mixture of NSS and SPS. This study included: 1) A screening level investigation of SPS, NSS, and CS settling in 1-liter graduated cylinders and subsequent sludge concentration (Phase I); 2) A preliminary evaluation of the effect of various settling vessels, including a 3.2-liter column, 2-liter beaker, and 1-liter Imhoff cone, on SPS and CS settling and subsequent sludge concentration (Phase II); 3) An investigation of CS settling in 1-liter graduated cylinders and subsequent sludge concentration at four separate settling times: 0.5, 1.0, 3.0, and 5.6 hours (Phase III); 4) An investigation of the WCH effect on CS settling and sludge concentration in four, 2-liter columns at four separate volumes and initial WCHs of 500 mL and 9.5 cm, 1,000 mL and 20.9 cm, 1,500 mL and 30.4 cm, and 2,000 mL and 44.1 cm, respectively (Phase IV); 5) An investigation of the D:H ratio effects on CS settling and sludge concentration in different diameter vessels at a constant WCH (Phase V); 4) An investigation of the effects of dilute mannich polymer addition on CS settling and sludge concentration in 1-liter columns (Phase VI).

On average for all six phases, the raw SPS ranged from 0.16 to 3.83%; the raw NSS ranged from 0.59 to 2.59%; the raw CS ranged from 0.25 to 3.60%. The average %TS of raw SPS, NSS, and CS were 0.82%, 1.12%, and 0.83%, respectively (Table 2).

The benchmark of 5–6% total solids of concentrated sludge was achieved only seven times in the 133 tests performed on CS. Flotation problems were observed three times.

In Phase I, it was observed from passive settling tests in 1-L columns that SPS settled better than NSS. As expected, CS exhibited settling characteristics between both SPS and NSS. The sludges tested did not seem representative of normal plant operations and showed extremely inhibited settling. For example, the initial average %TS of CS (2.06%) was much more concentrated than the recommended design sludge concentration of 0.58%. In subsequent tests the average %TS of the CS ranged from 0.28 to 0.83. The results of Phase I should be viewed with caution (Table 3)

In Phase II, settling tests were performed on a more representative CS sludge (0.34%) in vessels of varying shapes and geometries. The 2-liter beaker resulted in the lowest sludge concentrations, whereas the 3.2-L stir column showed the highest sludge concentrations (2.56 %TS). Additionally, the conical bottom of the Imhoff cone did not increase the concentration as much as expected and performed similar to the 3.2-liter stir column. A high degree of settling was observed for each vessel as the *%ΔI* exceeded 90% within the first 30 minutes. On average, the vessels with the lowest D:H ratio and the highest initial WCH yielded the most concentrated sludge (Table 4).

In Phase III, it was observed that increasing settling time corresponded with increased solids concentration. At 0.5 hours, the CS settled to an average %TS of 2.04%. At the residence time consistent with the design of the new preliminary sludge thickening facility at the Stickney WRP of 5.6 hours, the CS settled to an average %TS of 2.84% (Table 5).

In Phase IV, it was observed that increasing the WCH and volume resulted in increased concentrated solids. At 500 mL and a WCH of 9.47 cm, the CS settled to an average %TS of 1.03%. At 2,000 mL and a WCH of 44.09 cm, the CS settled to an average %TS of 1.99%.

Based on the Phase IV results, the results suggest that the gravitational forces imparted by the overburden water column increases the concentration of the sludge. A model was fitted to a plot of WCH versus %TS (Figure 4a). Based on a WCH of 23 feet for the design concentration tanks at the Stickney WRP, the model predicted a concentrated sludge of 3.98%. Because each settling column had the same diameter, the same relationship between 1) WCH and %TS and 2) volume and %TS was observed (Table 6).

However, these tests were performed with columns that had very low D:H ratios of 0.22–0.69. The design tanks have a D:H ratio of 3.48. The Phase IV tests indicated that the %TS of concentrated sludge decreased with increasing D:H values. Using a model fitted to these results and applying it to the design tank D:H, a predicted %TS value closer to zero was calculated (Figure 4b). In the Phase IV setup, decreasing tested volumes were accompanied by increasing D:H ratios. As such, the lower volumes and thus shallower waters with the higher D:H ratios resulted in less compressive forces, thereby leading to lower %TS in the settled blanket.

In Phase V, settling tests were performed to minimize the water column effect and to further evaluate the effect of D:H on settling. Vessels varying in diameter from 5.9 cm to 26.8 cm were examined at the same sludge fill height of 36.4 cm. All tests had a settling time of 5.6 hours (Table 7). It was observed that as D:H and volume increased, %TS of the settled sludge increased. A D:H ratio of 0.16 resulted in a final sludge concentration of 2.51%, whereas a D:H ratio of 0.74 resulted in a concentration of 3.15%. A logarithmic trend was observed, and concentrations did not increase significantly above a D:H ratio of 0.56.

In Phase VI, dilute mannich polymer was added to one liter of CS at the following doses: 0 mL, 0.1 mL, 0.3 mL, 0.5 mL, 0.7 mL, and 0.9 mL. Settling tests were subsequently performed on the treated sludge. All tests had a settling time of 5.6 hours (Table 8). The highest concentrated solids were observed at the 0.3 mL polymer dose, but the difference in the %TS of the settled sludge among all treatments was minimal. An average settled sludge concentration of 3.33% was observed for the control (no polymer addition) and 3.55% was observed for the 0.3 mL polymer addition treatment.

Based on these settling tests, flotation problems are of minimal concern. However, the 5–6 %TS benchmark for the designed concentration tanks was achieved in the passive settling tests only 5.3% of the time. Increased volumes and WCHs did enhance concentration up to certain limits, but diminishing returns were observed beyond these limits. Therefore, it is difficult to predict how significant the effect of the large volumes and WCHs of the design tanks would have on CS settling. As the D:H ratio is a function of both WCH and test volume for the size of vessels used, it is difficult to use it as a stand alone variable in predicting the effect on settling. Additionally, dilute mannich polymer addition was not observed to have a significant impact on the concentration of the settled sludge.

Most of the tests indicated extensive settling within the first 30 minutes. However, there were enough occurrences of inhibited settling in the first 30 minutes which would warrant longer settling times. It was observed that in cylindrical columns, increasing diameters paralleled higher settling velocities within the first 30 minutes of settling. However, it is difficult to suggest how passive settling velocities would mimic that of full-scale dynamic concentration tanks. Full-scale studies may need to be performed to truly evaluate the settling characteristics of CS.