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EVALUATION OF THE VORTEX CONCENTRATOR FOR CONTROLLING SUSPENDED SOLIDS IN SURFACE RUNOFF

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Abstract: The use of vortex concentrators is becoming increasingly popular for suspended solids reduction in combined sewer overflows and storm sewer discharges. This study is a laboratory investigation of the use of vortex concentrators to reduce the solids concentration of synthesized wastewaters. The synthesized wastewaters were made with tap water and addition of three particle types, sand, granular activated carbon, or sewage solids, which were collected, dried, graded by wet sieve size, and resuspended. These solids were collected from either a combined sewer overflow or storm sewer discharge. The range of surface loadings investigated was 120 to 850 $m^3/m^2 \cdot day$, and suspended solids concentrations were varied from 300 to 5,000 mg/L. The laboratory vortex concentrators were operated without addition of coagulant or with addition of polyacrylamide (PAM). Sand particles in the intermediate size range of 90 to 150 μm were reduced 59% without coagulant addition. Granular activated carbon particles in the intermediate size range of 150 to 300 μm were reduced 65% without coagulant addition. In both type particles, larger diameter sizes were removed more completely and smaller sizes less completely. Sewage solids suspensions were tested in two size ranges, less than 45 μm and 45 to 250 μm. These particles were from either combined sewers or storm sewers. Reductions ranged from 46% for small solids without coagulant addition to 94% for large solids with coagulant addition. Also reported are the effect of hydraulic retention time, suspended solids concentration, ratio of overflow to foul flow (i.e., underflow).

Key Words: polyacrylamide, surface loading rate, suspended solids, vortex concentrator

INTRODUCTION

The significance of pollution caused by storm water runoff has been well documented. A large portion of this pollution is associated with overflows or relief in combined and separated sewer overflows. The storm water containing this high initial pollutant load is called the first flush phenomenon.[1)] During the first flush, an enormous quantity of pollutants is discharged into the receiving waters.[2,3)] The first flush effect is considered to be more prevalent on impervious areas than on pervious areas. The most common pollutant during the

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first flush is suspended solids(SS). SS is the most important storm water runoff pollutant in terms of mass and has additional significance because other pollutants, such as heavy metals, are primarily associated with fine particles.4) Urban storm water runoff from paved surfaces transports a wide gradation of solids ranging in size from smaller than 1 μm to greater than 10,000 μm.5) The gravity settling velocity of the solids matters consisted of smaller than 200 μm is too slow, so another process is needed for removal of these fine particles, such as flocculation. Many devices have been developed for storm water control. Among these devices, the vortex or swirl concentrator has been popular. In the 1970s, the US.EPA completed a series of projects to development and demonstrate swirl settleable-solids removal technology.6) Subsequently, a new generation of vortex technology has developed, including the Swirl-Flo, Storm-King, Fluidsep, ActiFlo, Grit-King, Swirl-degritter.7~11) In spite of design and application differences, the main intent of these technologies are the same, that is, to separate settleable solids from the storm water by a vortex or swirling flowfield.6) The advantages of the vortex concentrator (or swirl concentrator) include no moving parts, no external power requirement, and operation at high hydraulic loadings, which results in compact size and low operation cost.8,12) The major objectives of this study were twofold. First, design and development of operating procedures for laboratory scale vortex concentrators. Second, determination of the optimum operation parameter such as surface loading rate, the ratio of the foul flow rate to influent.

MATERIALS AND EXPERIMENTAL METHOD

Materials

Sullivan et al.10,13) conducted a modeling study to determine if the modified swirl concentrator could be used to provide primary treatment to combined sewer overflows, municipal wastewater, and erosion treatment. This hydraulic model studies were based on synthetic solid made of Petrothene (SG=0.95), and Gilsonite (SG=1.06). By means of this modeling test, they determined the settling characteristics of solids to provide laboratory control and prototype swirl size, and shape. In this study sand (to simulate heavy material) and granular activated carbon (to simulate lighter material) were chosen as the solids with well defined characteristics. Combined sewer and storm sewer sediments were chosen to closely simulate the combined sewer overflow and storm water overflow solids. The grain size ranges of sand (SG=2.65) were 150~300 μm, 90~150 μm, and 45~90 μm. The granular activated carbon (SG=1.3) grain size ranges were 300~600 μm, 150~300 μm and 74~150 μm. The sewage and storm sewer sediments grain size ranges were <45 μm and 45~250 μm. After drying these solids were fractionated according to particle size using wet sieve and then diluted with tap water by various SS concentration like as storm water runoff. Graded materials were vigorously mixed with tap water and stored in a raw wastewater tank, which was mixed continuously using a mixer in order to obtain homogeneity. The samples were taken simultaneously at the influent storage tank and overflow treated water storage tank and measured by mass of solids retained on a GF/C filter after 2 h of drying at 105℃.

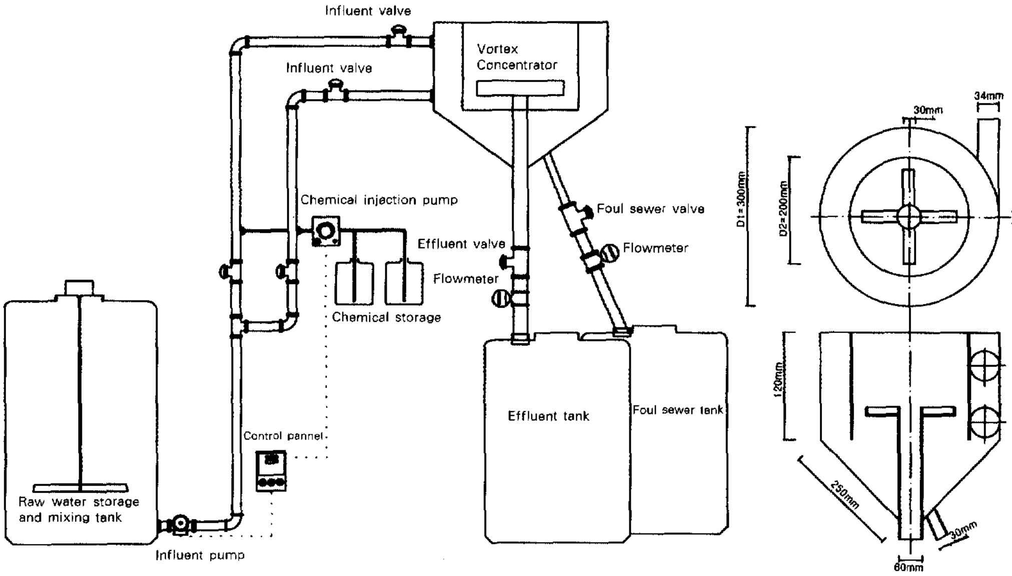
Vortex Concentrator Process Description

A vortex concentrator was used in this study. However, the results also apply to swirl concentrators, because the main intent and treatment theory is the same, that is, to separate settleable solids from the wastewater by vortex or swirling flow field. The main differences are shown in Table 1.12,13)

The raw wastewater is introduced tangentially through an entry port approximately halfway up the chamber wall, so that the solids rotate about the vertical axis of the vessel. This first

Table 1. The principal structural difference between vortex and swirl concentrator

Different items	Vortex concentrator	Swirl concentrator
Slope of bottom floor	Conical central hopper with 60 degrees to floor	Slope with 1:10 like as conventional sedimentation basin
Overflow weir	Four rectangular weirs are connected the central down shaft	Weir plate is a horizontal circular plate that connects the overflow weir to the central down shaft
Floatable trap	None	A surface flow deflector extends across the outer chamber wall
Vertical inner skirt	Supported by the chamber's vertical axis, divided the chamber into two concentric sectors	None



(a) diagram (b) vortex chamber

Figure 1. Schematic diagram of the vortex concentrator and detailed vortex chamber.

flow field allows the solids to settle out by gravity. A second vortex is generated in an inner skirt, which directs the solids towards the bottom and center. The laboratory vortex concentrator system consisted of raw wastewater storage tank, valves, coagulant influent pump, coagulant injection pump, vortex chamber, effluent, and foul flow storage tank, which are illustrated in Figure 1. The vortex chamber was made of acryl resin, and the inner diameter and height were 300 mm, 230 mm, respectively. The inner skirt diameter was 230 mm. The bottom of this chamber was a 60 slope conical bottom with 50 mm effluent pipe and 30 mm foul flow pipe. The inlet pipe for the chamber was 30 mm in diameter. Influent enters the vortex tangentially and following the peripheral wall of the cylindrical chamber creating a vortex flow pattern. The vortex flow action causes settleable solids to be concentrated at the bottom. The down shaft pipe was 300 mm in diameter, and had four rectangular weirs attached. Flow was measured in the effluent and the effluent overflow pipe by means of digital flow meter. The synthetic SS was introduced into the inlet pipe and mixed in the line with coagulant by means of a coagulant injection pump. Flowrate was controlled by an influent valve and a foul flow drainage valve.

Process Operation

The experiment was repeated with different amounts of solids added in the raw wastewater storage tank. Surface loading rates, detention times, and the ratio of foul flow to inflow were varied by adjusting the valves. Process operation for initial period of three minutes was sufficient to attain steady state conditions. The range of surface loading rate was 120~850 $m^3/m^2 \cdot$day. The influent SS concentration varies from 300~5,000 mg/L. Studies were conducted both without and with coagulant addition. During the experimental runs, SS removal efficiency E(%), was calculated by Equation (1),

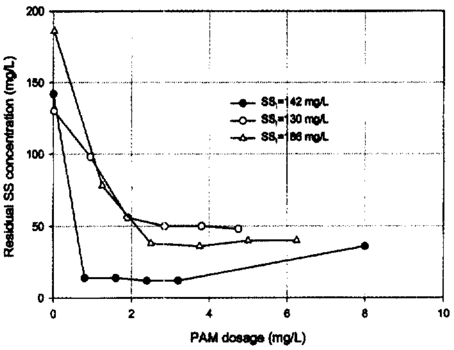
$$E(\%) = \frac{S_I V_I - S_o V_o}{S_I V_I} \times 100\% = \frac{M_I - M_o}{M_I} \times 100\% \qquad (1)$$

where $M_I = S_I V_I$ = mass of untreated influent solids; and $M_o = S_o V_o$ = mass of treated effluent solids. S_I and S_o are the SS concentrations of the synthetic wastewater samples taken from inlet, and outlet, respectively.

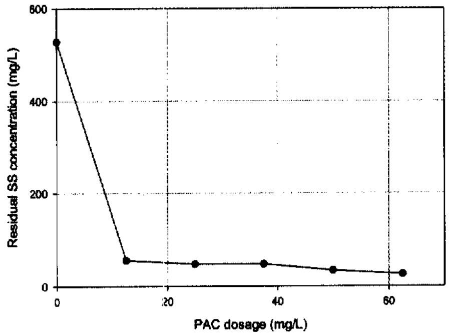
RESULTS AND DISCUSSION

Coagulant Type and Dosage

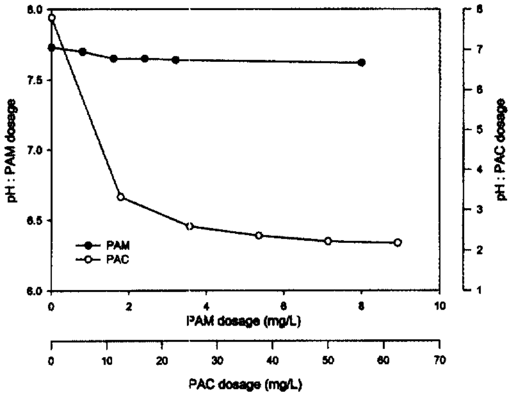
The coagulant dosage was determined by means of conventional six position jar test apparatus for treatment of sewage and storm water sediment. Solids samples were vigorously stirred, before the experimental runs to obtain homogeneity. The chemical coagulants used polyacrylamide (PAM: commonly used as a soil erosion control) and poly aluminum chloride (PAC: commonly used as a water treatment coagulant) were pure grade.[14] Rapid mixing at 200 rpm for 1 min was provided after chemical addition. The mixing speed was then reduced to 60 rpm and slowly mixed for 5 min for flocculation. After 15 min quiescent settling, a sample of supernatant was taken from below the surface and used for residual SS measurement. The range of SS concentrations before treatment was 318~338 mg/L for sewage sediment wastewater, and 136~166 mg/L for storm water sediment wastewater. The results of the experimental runs with varying PAM and PAC dosage for sewage and



(a) PAM



(b) PAC



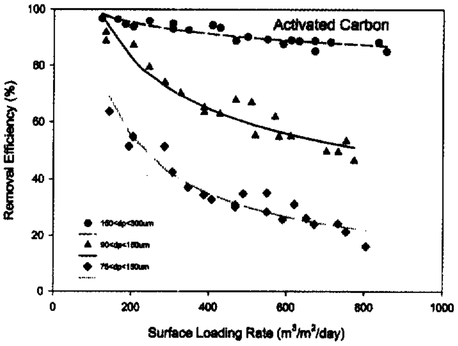
(c) pH variation for each coagulant

Figure 2. Determination of optimum chemical dosage.

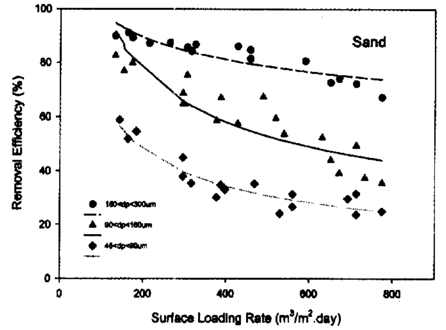
Table 2. Optimum coagulants dosage and SS removal efficiency

Coagulants	Initial SS (mg/L)	Optimum dosage (mg/L)	Removal efficiency (%)
PAM	142	2.4~3.2	99
	130	4.8	96
	186	3.8	97
PAC	528	62.5	98

storm water sediment wastewater samples are shown in Figure 2(a), (b), respectively. As shown in the figure, the SS removal efficiency improves as the dosage of PAM was increased from 1 mg/L to 2~3 mg/L. The removal efficiency of SS almost remained constant as the PAM was increased from 3 mg/L to 4 mg/L. The optimum coagulants dosage and SS removal efficiency were summarized in Table 2. The optimum coagulant for PAM was approximately 2 mg/L, in this condition the ranges of the SS removal efficiency was 96~99%. Due to high PAC dosage requirement, PAM was used as the coagulant for this study. Figure 2(c) illustrated variation of pH values with different concentration of coagulant. The pH value rapidly decreases from 8 to 2 for PAC, but pH value was mostly steady for PAM. Which further supported the selection of PAM for the vortex concentrator coagulant.



(a) graded activated carbon



(b) graded sand

Figure 3. Removal efficiency as function of surface loading rate for activated carbon and sand.

Surface Loading Rate

The removal efficiency with variation of a surface loading rate for sand and activated carbon solids is provided in Table 3. During the experimental runs, SS removal efficiency $E(\%)$, was calculated by Equation (1). SS removal efficiency results for activate carbon and sand are in Figure 3, as a function of surface loading rate, for three particle size groups.

Results showed that the average removal efficiency of the granular activated carbon was 91.2%, 65.4%, 34.8% for 300~600 μm, 150~300 μm, 75~150 μm particle size ranges, respectively, at surface loading rate of 122~856 $m^3/m^2\cdot$day. At surface loading rate of 132~774 $m^3/m^2\cdot$day, for 150~300 μm, 90~150 μm, 45~90 μm sand particle size ranges obtained the average removal efficiency for

Table 3. Removal efficiency for sand and activated carbon as a function of surface loading rate

Items	Particle size range (μm)					
	Granular activated carbon			Sand		
	300~600	150~300	75~150	150~300	90~150	45~90
$E(\%)$	85.0~96.7 (91.2)	46.5~91.8 (65.4)	16.1~63.6 (34.8)	67.2~91.2 (82.5)	35.5~82.6 (59.4)	23.8~58.8 (35.8)
$V_o(m^3/m^2/day)$	122~856 (467)	132~774 (461)	143~805 (481)	132~774 (415)	132~774 (459)	143~774 (445)

sand were 82.5%, 59.4% and 35.8%, respectively. Generally these results indicated that the particles removal efficiency be proportioned to particle size at the same specific gravity condition. At the same particle size, the removal efficiency for sand as higher than granular activated carbon about 15～18%. The relationship between particle size and average removal efficiency was plot in Figure 4, and these correlation equations are as following;

$$E(\%) = \frac{d_p}{1.66 + 0.005 d_p} \quad \text{: granular activated carbon} \tag{2}$$

$$E(\%) = \frac{d_p}{1.02 + 0.005 d_p} \quad \text{: sand} \tag{3}$$

Because the most portion of storm water runoff consisted mainly of sand with 150～300 μm size,[3)] the SS removal efficiency of the vortex concentrator could be estimated about 65% (82.5%×50% + 59.4%×25% + 35.8%×25% = 65%).

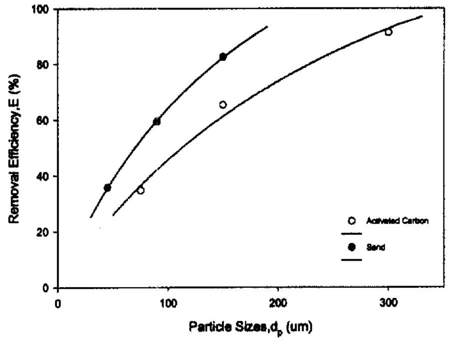
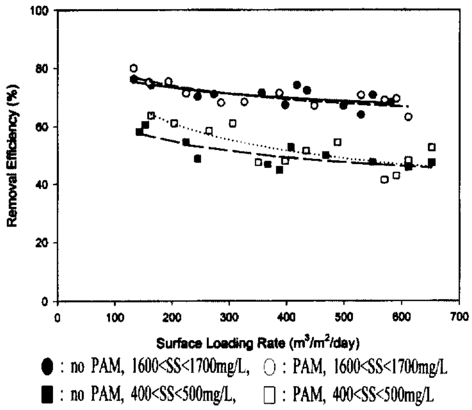


Figure 4. Removal efficiency as a function of particle sizes.

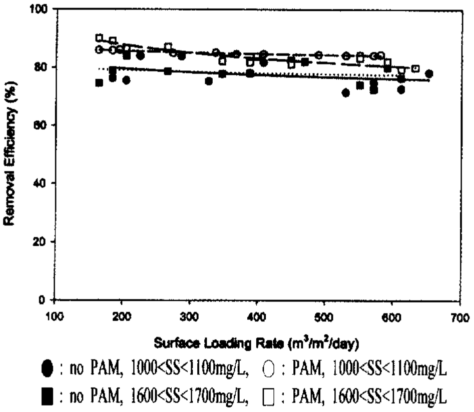
The vortex concentrator was tested for its ability to treat more realistic synthetic wastewaters made from sewage and storm water solids. The ranges of particle sizes were less than 45 μm, and 45～250 μm for each of the sewage sediment and storm water sediment solids. The vortex concentrator was operated with and without PAM, and the performance results shown in Table 4. PAM was run with average concentration of 2 mg/L that determined by jar tests. The average removal efficiency for less than 45 μm sewage sediment solids were 60.4% without PAM, 61.7% with PAM, respectively, thus no benefit from PAM. At same particle size, the average removal efficiency of storm water sediment solids were 45.6% without PAM, and 55.9% with PAM, thus a 10% improved with PAM. For particle sizes range of 45～250 μm, the

Table 4. Vortex concentrator operation range and SS removal efficiency for synthetic wastewater

Material solids	Particle size (μm)	V_o (m^3/m^2/day)	HRT (sec)	Influent		Effluent		Q_F/Q_o (%)	E (%)	Chemical
				Q_I (L/min)	SS_I (mg/L)	Q_o (L/min)	SS_o (mg/L)			
Sewage sediment	<45	132～652 (392)	11～55 (24)	6.5～32.0 (19.2)	414～1708 (1066)	4.7～30.2 (17.1)	163～616 (361)	6.0～38.3 (15.8)	44.8～76.2 (60.4)	None
	<45	132～652 (395)	11～55 (23)	6.5～32.0 (19.4)	446～1638 (1055)	4.7～30.2 (17.3)	187～598 (352)	6.0～38.3 (15.3)	41.4～80.0 (61.7)	PAM
	45～250	163～652 (401)	11～45 (22)	8.0～32.0 (19.7)	1000～1654 (1352)	6.2～28.2 (17.5)	176～463 (298)	6.4～29.0 (14.4)	71.4～83.9 (78.0)	None
	45～250	163～632 (392)	12～45 (23)	8.0～31.0 (19.3)	1016～1716 (1351)	6.2～29.2 (17.1)	102～269 (210)	6.2～29.0 (15.0)	79.3～90.0 (84.3)	PAM
Storm water sediment	<45	183～591 (375)	12～40 (23)	9.0～29.0 (18.4)	352～1280 (732)	7.2～27.2 (16.2)	167～801 (391)	6.6～25.0 (14.8)	36.8～61.8 (45.6)	None
	<45	143～652 (379)	11～51 (25)	7.0～32.0 (18.6)	358～1173 (715)	5.2～30.2 (16.5)	133～478 (308)	6.0～34.6 (16.3)	48.0～69.7 (55.9)	PAM
	45～250	122～827 (439)	9～60 (21)	6.0～40.6 (21.5)	424～5174 (2283)	5.1～38.4 (18.6)	165～1714 (758)	1.6～76.5 (19.0)	42.8～81.8 (63.8)	None
	45～250	191～615 (392)	12～38 (22)	9.4～30.2 (19.2)	922～1298 (1121)	7.6～28.4 (17.4)	49～76 (62)	6.3～23.7 (12.5)	93.3～95.4 (94.4)	PAM



(a) particle size <45 μm



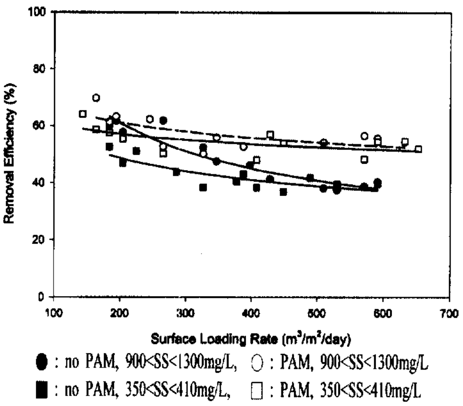
(b) range of particle size 45~250 μm

Figure 5. SS removal efficiency for sewage sediment.

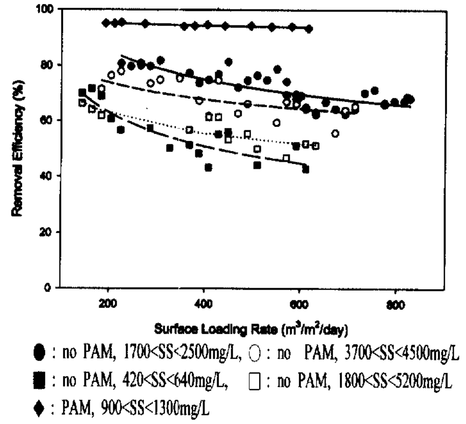
average removal efficiency for sewage sediment solids were 78.0% without PAM, 84.3% with PAM. In case of storm sewer sediment were 63.8% without PAM and 94.4% with PAM. The variation of the removal efficiency for sewage and separated sewer sediment as a function of surface loading rate were plotted in Figures 5 and 6, respectively. As shown in the figures, PAM was beneficial for small solids, but provided no benefit for high influent SS concentration.

Hydraulic Retention Time

The hydraulic retention time (HRT) of the vortex concentrator is very short compared with conventional sedimentation basin, therefore it requires less land space. The SS removal efficiency increases with the HRT, till it reaches a time around 40 sec, after this time efficiency reaches steady state as shown in Figure 7. The removal efficiency was improved slightly with PAM for these small solids.



(a) particle size <45m



(b) range of particle size 45~250 μm

Figure 6. SS removal efficiency for storm sewer sediment.

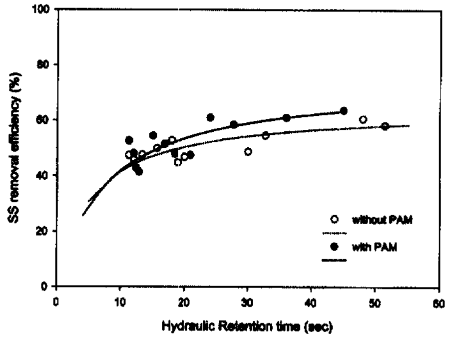


Figure 7. Removal efficiency as a function of HRT for storm water sediment, size <45 μm.

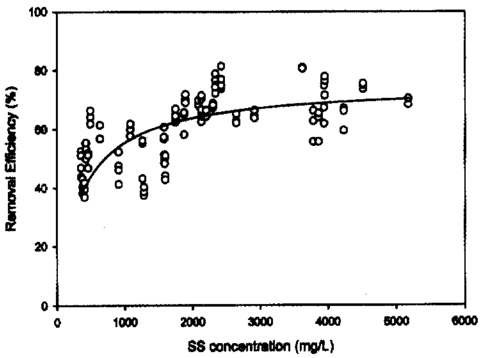


Figure 8. The relationship between the influent SS concentration and removal efficiency.

Influent SS Concentration

The relationship between the removal efficiency and the influent concentration for storm water sediment solids is shown in Figure 8. The removal efficiency was increased with increased SS concentration. In case of activated carbon and sand showed same pattern. During the first flush the SS concentration range is higher than 1,000 mg/L, therefore if SS concentration was 1,000 mg/L, the removal efficiency would be estimated 70% for combined sewer overflow and 65% for storm sewer overflow.

Ratio of the Foul to Overflow

The ratio of the foul to overflow, Q_F/Q_o is a major parameter for vortex concentrator operation. The range of this ratio based on other researchers is usually from about 5% to 25%.[6,13,15] Field et al.[6] suggest that the foul flow ranges from 6% to 10% of influent and Sullivan et al.,[13] Paul[15] suggest 10~20%, 10~25% of overflow, respectively. The transported wastewater flow increases at treatment plant and deposits of solids on the bottom of the vortex chamber reduced gradually as the foul to overflow ratio was increased. Sullivan et al.[13] reported that the efficiency increased with this ratio. The relationship between Q_F/Q_o and removal efficiency for particle size less than 45 μm sewage sediment solids is shown Figure 9.

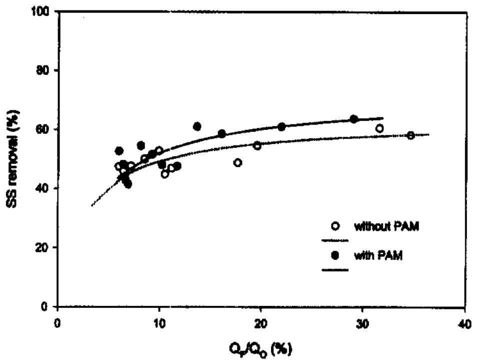


Figure 9. The relationship between the ratio of Q_F/Q_o and removal efficiency.

Generally the removal efficiency was increased with Q_F/Q_o. This indicates that gravity settling flux was increased in proportion with Q_F/Q_o and reduced the surface loading rate, therefore prevent the resuspension of settled solids. According to other test results, removal efficiencies were increased with the draw-off. In case of activated carbon (data not shown) the Q_F/Q_o influenced to small particle more than large particle.

Follow-up Treatment

Figure 8 summarizes the vortex concentrator removal efficiency for different influent SS concentrations. For example, at an influent SS concentration of 1,500 mg/L, the vortex concentrator effluent would be about 600 mg/L. A lower surface loading would improve this somewhat, but that would require a much large and more expensive vortex concentrator. An alternative solution to improve treatment might be a follow-up settling basin.

To examine the alternative, a series of settling test was performed on the treated overflow water from the vortex concentrator. Treated water was filled in 1 L beaker and sampled every 5 min three times. The object of this test was to determine the HRT needed for follow-up settling basin. The result was summarized in Table 5 for sewage and storm water sediment particle.

Figure 10 is an example result of test that shown variation of SS concentration for 45~250 μm sewage solids. During the initial 5

Table 5. SS removal efficiency as function of settling time (unit: %)

Settling time (min)	d_p <45 μm		45<d_p<250 μm	
	No PAM	PAM	No PAM	PAM
5	31.6~41.0 (37.6)	36.8~55.3 (46.1)	54.2~74.6 (63.8)	4.8~79.7 (53.7)
10	47.9~59.7 (53.2)	50.0~66.3 (57.3)	68.3~86.6 (74.4)	28.6~83.7 (69.2)
15	49.4~64.7 (58.1)	51.5~70.6 (63.7)	70.0~95.5 (80.3)	33.3~85.9 (73.2)

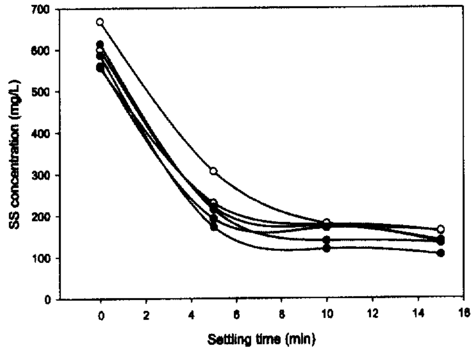


Figure 10. The variation of the SS concentration with settling time.

min, the particles were rapidly removed. This suggests that 5 to 10 min HRT in a follow-up settling basin would substantially improve the results.

CONCLUSIONS

This study was a laboratory investigation of the vortex concentrator. Synthetic wastewaters were made with sand, granular activated carbon, and solids collected from a combined sewer overflow (i.e., sewage solids) and storm water discharge (i.e., storm solids). The grain size range of sand (SG=2.65) particles was 150 ~300 μm, 90~150 μm, 45~90 μm; granular activated carbon (SG=1.3) particles was 300~600 μm, 150~300 μm, or 74~150 m; sewage and storm sediments were <45 μm, or 45~250 μm. The results of the vortex concentrator operation are summarized as following;

1. The optimum coagulant and dosage for PAM was 2 mg/L.
2. The SS removal efficiency for 150~300 μm size sand grain was about 65%.
3. The range of removal efficiency for <45 μm sewage and storm sediment solids was 45.6% to 61.7%, and the range of removal efficiency for particle sizes in the range of 45~250 μm was 63.8% to 94.4%.
4. The removal efficiency was increased with increase of HRT, and the optimum HRT was 40 to 60 sec.
5. The removal efficiency was better for higher initial SS concentrations.
6. The removal efficiency was increased with higher ratio of foul to overflow, and its influence was greater for small particles.
7. The vortex concentrator was operated with high surface loading rate condition.

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