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Screening and evaluation of polymers as flocculation aids for the treatment of aquacultural effluents[☆]

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Abstract

As environmental regulations become more stringent, environmentally sound waste management and disposal are becoming increasingly more important in all aquaculture operations. One of the primary water quality parameters of concern is the suspended solids concentration in the discharged effluent. For example, EPA initially considered the establishment of numerical limitations for only one single pollutant: total suspended solids (TSS). For recirculation systems, the proposed TSS limitations would have applied to solids polishing or secondary solids removal technology. The new rules and regulations from EPA (August 23, 2004) require only qualitative TSS limits, in the form of solids control best management practices (BMP), allowing individual regional and site specific conditions to be addressed by existing state or regional programs through NPDES permits. In recirculation systems, microscreen filters are commonly used to remove the suspended solids from the process water. Further concentration of suspended solids from the backwash water of the microscreen filter could significantly reduce quantity of discharge water. And in some cases, the backwash water from microscreen filters needs to be further concentrated to minimize storage volume during over wintering for land disposal or other final disposal options. In addition, this may be required to meet local, state, and regional discharge water quality. The objective of this research was an initial screening of several commercially available polymers routinely used as coagulation–

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flocculation aids in the drinking and wastewater treatment industry and determination of their effectiveness for the treatment of aquaculture wastewater. Based on the results of the initial screening, a further evaluation of six polymers was conducted to estimate the optimum polymer dosage for flocculation of aquaculture microscreen effluent and overall solids removal efficiency. Results of these evaluations show TSS removal was close to 99% via settling, with final TSS values ranging from as low as 10–17 mg/L. Although not intended to be used for reactive phosphorus (RP) removal, RP was reduced by 92–95% by removing most of the TSS in the wastewater to approximately 1 mg/L-P. Dosage requirements were fairly uniform, requiring between 15 and 20 mg/L of polymer. Using these dosages, estimated costs range from \$4.38 to \$13.08 per metric tonne of feed.

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Keywords: Waste management; Polymers; Flocculant aids

1. Introduction

Microscreen filters have become very popular for suspended solids removal, because they require minimal labor and floor space and can treat large flow rates of water with little head loss (Cripps and Bergheim, 2000; Timmons et al., 2002). Screen filters remove solids by virtue of physical restrictions (or straining) on a media when the mesh size of the screen is smaller than the particles in the wastewater. Microscreen filters, though, generate a separate solids waste stream that must be further processed before final discharge. The backwash flow volume and solids content will vary based on several factors. These are the screen opening size, type of backwash control employed, frequency of backwash, and influent total suspended solids (TSS) load on the filter (Cripps and Bergheim, 2000). Backwash flow is generally expressed as a percentage of the flow the filter treats, with reported backwash flows ranging from 0.2 to 1.5% of the treated flow (Ebeling and Summerfelt, 2002). TSS concentration of the backwash flow are on the order of 1000 mg/L, although this can vary depending upon screen mesh size, flow rate, initial concentration and maintenance, among other factors (Ebeling, unpublished data).

Phosphorus is one of the most scrutinized nutrients discharged by aquaculture systems, due to its impact on receiving bodies of water. Phosphorus is often the limiting nutrient in natural ecosystems, and excessive algae blooms can occur if discharge concentrations exceed the absorption capacity of the receiving body of water. It has been demonstrated that 30–84% of the total phosphorus discharged from aquaculture systems is contained in the solids fraction (Cripps and Bergheim, 2000). Thus any mechanism that could enhance solids removal would also contribute to a reduction in the overall level of phosphorus discharge.

In many cases, the backwash water from microscreen filters needs to be further concentrated to minimize solids storage volume requirements during over wintering, for land disposal, or other final disposal options. To accomplish this, a variety of technologies have been employed, ranging from simple settling cones (Ebeling and Summerfelt, 2002) to sophisticated belt filters (Ebeling et al., 2004a). In order to improve the settling characteristics and performance of other filtration technologies, the particle size of the microscreen discharge can be increased by the addition of coagulation/flocculation aids (Ebeling et al., 2003, 2004b). Coagulation and flocculation processes with aids such as

alum and ferric chloride are standard techniques in the wastewater and drinking water industry for removal of suspended solids. Recently, the use of high molecular weight long-chain polymers has been used as replacement to alum and ferric chloride for flocculation of suspended solids. Advantages of the polymers are:

- lower dosage requirements;
- reduced sludge production;
- easier storage and mixing;
- both the molecular weight and charge densities can be optimized creating ‘designer’ flocculant aids;
- no pH adjustment required;
- polymers bridge many smaller particles;
- improved floc resistance to shear forces.

In the past, these coagulation/flocculation aids have not been extensively applied in the aquaculture industry primarily, because of the dilute nature of most aquaculture waste streams. However, the concentrated waste stream from recirculating systems, especially the backwash from microscreen filters, makes this option feasible from both engineering and economic viewpoints.

Polymers or polyelectrolytes consist of simple monomers that are polymerized into high-molecular-weight substances (Metcalf and Eddy, 1991) with molecular weights varying from 10^4 to 10^6 Da. Polymers can vary in molecular weight, structure (linear versus branched), amount of charge, charge type and composition. The intensity of the charge depends upon the degree of ionization of the functional groups, the degree of copolymerization and/or the amount of substituted groups in the polymer structure (Wakeman and Tarleton, 1999). With respect to charge, organic polymers can be cationic (positively charged), anionic (negatively charged) or nonionic (no charge). Polymers in solution generally exhibit low diffusion rates and raised viscosities, thus it is necessary to mechanically disperse the polymer into the water. This is accomplished with short, vigorous mixing (velocity gradients, G-values of 1500 s^{-1} , although smaller values have been reported in the literature, $300\text{--}600 \text{ s}^{-1}$) to maximize dispersion, but not so vigorous as to degrade the polymer or the flocs as they form (Wakeman and Tarleton, 1999).

The effectiveness of high molecular weight long-chain polymer treatment of aquaculture wastewater depends on the efficiency of each stage of the process: coagulation, flocculation, and solids separation. In turn, the process efficiency can depend on:

- polymer concentration;
- polymer charge (anionic, cationic, and nonionic);
- polymer molecular weight and charge density;
- raw wastewater characteristics (particle size, concentration, temperature, hardness, and pH);
- physical parameters of the process (dosage, mixing energy, flocculation energy, and duration);
- discharge water treatment levels required.

Polyelectrolytes act in two distinct ways: charge neutralization and bridging between particles. Because wastewater particles are normally charged negatively, low molecular weight cationic polyelectrolytes can act as a coagulant that neutralizes or reduces the negative charge on the particles, similar to the effect of alum or ferric chloride. This has the effect of drastically reducing the repulsive force between colloidal particles, which allows the van der Waals force of attraction to encourage initial aggregation of colloidal and fine suspended materials to form microfloc. The coagulated particles are extremely dense, tend to pack closely, and settle rapidly. If too much polymer is used, however, a charge reversal can occur and the particles will again become dispersed, but with a positive charge rather than negatively charged.

Higher molecular weight polymers are generally used to promote bridging flocculation. The long chain polymers attach at a relatively few sites on the particles, leaving long loops and tails which stretch out into the surrounding water. In order for the bridging flocculants to work, the distance between the particles must be small enough for the loops and tails to connect two particles. The polymer molecule thus attaches itself to another particle forming a bridge. Flocculation is usually more effective the higher the molecular weight of the polymer. If too much polymer is used, however, the entire particle surface can become coated with polymer, such that no sites are available to 'bridge' with other particles, the 'hair-ball effect'. In general, high molecular weight polymers produce relatively large, loosely packed flocs, and more fragile flocs (Wakeman and Tarleton, 1999).

Because the chemistry of wastewater has a significant effect on the performance of a polymer, the selection of a type of polymer for use as a coagulant/flocculation aid generally requires testing with the targeted waste stream and the final selection is often more of an 'art' than a science. Hundreds of polymers are available from numerous manufactures with a wide variety of physical and chemical properties. And, although the manufactures can often help in a general way, the end user must often determine from all the various product lines which is best for their particular application and waste stream, i.e. most cost-effective. This paper presents the results of a series of tests that were conducted to screen a wide range of commercially available polymers and then evaluated the performance of a small subset that showed potential for use with aquaculture microscreen backwash effluent. It by no means intended to be a comprehensive review, but to show the potential of polymers to be used as the sole coagulant/flocculant aid for microscreen backwash effluent.

2. Materials and methods

2.1. Screening

Three commercial sources of polymers for the wastewater industry were contacted and samples obtained of recommended polymers for aquaculture wastewater. The companies were: Ciba Specialty Chemicals Corporation, <http://www.cibasc.com>; Cytec Industries Inc. <http://www.cytec.com>; and Hychem Inc., <http://www.hychem.com>. Table 1 lists the individual polymers supplied, the chemical family, charge, molecular weight and form based on data from either product description information or Material Safety Data Sheets.

Table 1
Summary of screened polymers chemical family, charge, molecular weight and recommended dosages

Trade name	Chemical family	Charge	Molecular weight	Maximum dosage of potable water (mg/L)	Form
Ciba Specialty Chemicals, 2301 Wilroy Road, Suffolk, VA 23434					
Magnafloc LT 7990	Polyamine	Very high degree of cationic charge	Very low	20	Liquid
Magnafloc LT 7991	Polyamine	Very high degree of cationic charge	Very low	20	Liquid
Magnafloc LT 7992	Organic cationic polyelectrolyte	Very high degree of cationic charge	Very low	50	Liquid
Magnafloc LT 7995	Organic cationic polyelectrolyte	Very high degree of cationic charge	Very low	25	Liquid
Magnafloc LT 7922	Acrylamide polymer or copolymer	Low degree of cationic charge	Very high	1	Liquid
Magnafloc LT 20	Polyacrylamide	Degree of nonionic charge	Medium	1	Powder
Magnafloc LT 22S	Copolymer of quaternary acrylate salt and acrylamide	Low degree of cationic charge	High	1	Powder
Magnafloc LT 25	Copolymer of sodium acrylate and acrylamide	Low degree of anionic charge	Medium	1	Powder
Magnafloc LT 26	Copolymer of sodium acrylate and acrylamide	Medium degree of anionic charge	Medium	1	Powder
Magnafloc LT 27	Copolymer of sodium acrylate and acrylamide	Medium degree of anionic charge	High	1	Powder
Magnafloc E 30	Polyacrylamide	Degree of nonionic charge	High	3.5	Liquid
Magnafloc E 32	Anionic polyacrylamide emulsion	Very low degree of anionic charge	High	3.5	Liquid
Magnafloc E 38	Anionic polyacrylamide emulsion	High degree of anionic charge	Very high	3.5	Liquid
Cytec Industries Inc., West Paterson, NJ					
SuperFloc A-120	Anionic Polyacrylamide	Low degree of anionic charge	High	1	Powder
SuperFloc A-130	Anionic Polyacrylamide	Medium degree of anionic charge	High	1	Powder
SuperFloc A-137	Polyacrylamide	High degree of anionic charge	High	1	Powder
Hychem Inc., 10014 N. Dale Mabry Highway, Suite 213, Tampa, FL 33618					
Hyperfloc CE 834	Cationic polyacrylamide	Medium degree of cationic charge	Very high	0.5–20 ^a	Liquid
Hyperfloc CE 854	Cationic polyacrylamide	High degree of cationic charge	Very high	0.5–20 ^a	Liquid
Hyperfloc CE 1950	Cationic polyacrylamide	High degree of cationic charge	Very high	0.5–20 ^a	Liquid

^a Recommended dosage level for settling/clarification

2.1.1. Jar tests

For over 50 years, the jar test has been the standard technique used to optimize the addition of coagulants and flocculants used in the wastewater and drinking water treatment industry (ASTM, 1995). Since polymer interactions are very complex, laboratory studies are used to determine the optimal dosage, duration, and intensity of mixing and flocculation. The coagulation–flocculation tests of the polymers were carried out following the standard practice for coagulation–flocculation testing of wastewater used to evaluate the chemicals, dosages, and conditions required to achieve optimum results (ASTM, 1995). Jar tests provide insight into the overall process effectiveness, particularly to mixing intensity and duration as it affects floc size and density, (Lee and Lin, 1999). Samples for jar tests were taken directly from the holding tank receiving the backwash water from two commercial size recirculating production systems growing arctic charr and rainbow trout. The first of these is a pilot-scale partial-reuse system consisting of three 3.66 m × 1.1 m deep circular ‘Cornell-type’ dual-drain culture tanks with a maximum feed loading rate of 45–50 kg of feed per day (Summerfelt et al., 2004a). The second system is a fully recirculating system consisting of a 150 m³ circular production tank with a maximum daily feed rate of 200 kg of feed per day (Summerfelt et al., 2004b). Water quality characteristics of the microscreen backwash effluent are summarized in Table 2.

A standard jar test apparatus, the Phipps & Bird Six-Paddle Stirrer with illuminated base (Fig. 1) was employed for the tests, with six 2-L square B-Ker² Plexiglas jars, sometimes called Gator Jars. The jars are provided with a sampling port, 10 cm below the water line, which allows for repetitive sampling with minimal impact on the test. The six flat paddles are all driven by a single variable speed motor from 0 to 300 rpm. An illuminated base helps observation of the floc formation and settling characteristics.

Stock solutions of the polymer flocculants were used to improve the ease of handling and measuring, and ensure good mixing in the jars. Stock solutions were prepared fresh each day following manufacturer’s recommendations, using either straight dilution or acetone dispersion methods for solid polymers. Simple dilutions of each polymer with spring water to a 0.2% solution by weight were mixed immediately before each test. Normally, the actual test procedures are representative of an existing treatment system, for example a wastewater treatment plant’s mixing, flocculation and settling tanks, in terms of

Table 2
Water quality characteristics of the microscreen backwash effluent

Parameter	Mean	S.D.	Range
pH	7.43	0.26	6.97–7.78
Temperature (°C)	19.4	1.4	18–21
Alkalinity (mg/L)	292	21	260–324
RP (mg/L–P)	12.3	5.7	6.0–22
TSS (mg/L)	1015	401	517–1540
TN (mg/L–N)	77.8	89.6	8–236
TAN (mg/L–N)	14.8	24.5	3.4–92
NO ₂ (mg/L–N)	0.43	0.34	0.23–1.36
NO ₃ (mg/L–N)	38.8	9.2	25.5–48.6
cBOD ₅ (mg/L)	548	190	281–947

Number of samples = 9.



Fig. 1. Phipps & Bird Six-paddle stirrer with illuminated base.

the duration of mixing and flocculation, the mixing speed, and settling time. In this broad screening study, standardized mixing and flocculation speeds and durations were used. For each jar test, the following procedure was followed (ASTM, 1995). Each jar was filled with 2 L of microscreen filter backwash sample measured with a graduated cylinder, and the initial temperature recorded. The polymer flocculant dose destined for each jar was carefully measured into syringes using an analytical balance. The multiple stirrer speed was set to the ‘flash mix’ value, i.e. maximum rpm (velocity gradient $\sim 400 \text{ s}^{-1}$), and the test solutions injected into the jars. After the predetermined ‘flash mix’ duration (10 s), the mixing speed was reduced to the flocculation or ‘slow mix’ value: 20 rpm for 10 min. After this time period, the paddles were withdrawn and the floc allowed to settle for 15 min. Samples were then withdrawn from the sampling ports located 10 cm below the water level for analysis.

2.1.2. Performance evaluation

For all of the screening tests, turbidity, and reactive phosphorus (RP, orthophosphate) were measured. For the purpose of polymer screening, turbidity was used as an indicator of suspended solids and orthophosphate for phosphorus content. Table 3 shows the methods used for each analysis. When appropriate, reagent standards and blanks were analyzed along with the samples to ensure quality control.

2.1.3. Screening results

In order to identify the effect of the polymer added, a control was carried through the jar test procedure. The percent reduction of the wastewater parameters of interest due to the treatment was calculated in relation to the untreated, unflocculated, but settled wastewater,

Table 3

Laboratory methods used for analysis via a Hach DR/2010 colorimeter

Parameter	Method/range
Alkalinity ^a	Standard methods 2320 B
Phosphorus, reactive ^b	Hach method 8048 (orthophosphate) 0–0.8 mg/L–P
Total suspended solids ^a	Standard methods 2540D
Turbidity ^a	Hach method 8237 0–450 NTU (nephelometric turbidity units)

^a Adapted from standard methods for the examination of water and wastewater (APHA, 1998).^b USEPA approved for reporting.

not to the raw wastewater. Table 4 shows the preliminary results of the screening tests conducted. Percent removal rates were calculated based on the maximum percent removal of turbidity up to the maximum dosage recommended for the treatment of potable water supplies, National Sanitation Foundation. Although in some cases high removal rates were seen at higher dosages, it was decided not to go beyond allowable dosage rates to insure minimum environmental risk with final disposal of the treated waste products.

Table 4

Preliminary screening performance results of polymers: turbidity and RP removal efficiency

Ciba Specialty Chemicals		Removal (%)		Maximum dosage (mg/L)
Trade name	Optimal dosage (mg/L)	Turbidity	RP	
Magnafloc LT 7990	No effect	–	–	20
Magnafloc LT 7991 ^a	20 ^b	89	53	20
Magnafloc LT 7992 ^a	20	84	47	50
Magnafloc LT 7995 ^a	10	84	47	25
Magnafloc LT 7922	1.0 ^b	48	45	1
Magnafloc LT 20	No effect	–	–	1
Magnafloc LT 22S ^a	1.0 ^b	91	48	1
Magnafloc LT 25	No effect	–	–	1
Magnafloc LT 26	No effect	–	–	1
Magnafloc LT 27	No effect	–	–	1
Magnafloc E 30	No effect	–	–	3.5
Magnafloc E 32	No effect	–	–	3.5
Magnafloc E 38	1.0	45	34	3.5
Cytac Industries				
SuperFloc A-120	No effect	–	–	1
SuperFloc A-130	1	35	7	1
SuperFloc A-137	0.5	40	6	1
Hychem Inc.				
Hyperfloc CE 834	50	87	10	0.5–20 ^c
Hyperfloc CE 854 ^a	25	98	73	0.5–20 ^c
Hyperfloc CE 1950 ^a	25	94	67	0.5–20 ^c

Removal (%) = [(settled – polymer treatment)/settled] × 100%.

^a Selected for further evaluation.^b Maximum recommended concentration for treatment of potable water (NSF).^c Recommended.

As can be seen from Table 4, there was a wide range of results from no effect on suspended solids to significant removal of suspended solids and significant impact on soluble reactive phosphorus. This underscores the need for testing of individual polymers with the actual wastewater stream. No general statements can be made, such as the difference between cationic and anionic charge or low or high molecular weight. For example, one of the highest removal efficiencies were from a polymer with a high cationic charge and very low molecular weight (Magnafloc LT 7991) and from a polymer with a low degree of cationic charge and a high molecular weight (Magnafloc LT 22S). Although not very high, Magnafloc E-38 showed some removal with a high degree of anionic charge and very high molecular weight. There was also no significant relationship between the family of the polymers, with almost all types tested showing some removal, and in one case (polyamine) showing both no effect and very significant effect on suspended solids (Magnafloc LT 7990 and LT 7991).

Fig. 2 shows an example of test results for Hyperfloc CE 854, cationic polyacrylamide copolymer emulsion with a high degree of cationic charge and a very high molecular weight. As can be seen from the figure, there is a substantial reduction in turbidity with only a small addition of polymer with an apparent minimum at a dosage of 25 mg/L. The increase in turbidity at higher dosages is typical of polymers and was seen in the some of the other samples tested. As described earlier, this is probably due to charge reversal of the particles. Fig. 3 shows the removal of soluble reactive phosphorus due to the removal of the filterable or settleable solids fraction, thus demonstrating that any mechanism that could enhance solids removal would also contribute to a reduction in the overall level of phosphorus discharge. Coagulant aids, such as alum and ferric chloride, remove phosphorus through a chemical reaction that binds the phosphorus to the metal ion. It is important to remember that unlike alum and ferric chloride, polymers are not intended to remove phosphorus directly, but can remove significant amounts by reducing the suspended solids concentration in the waste stream.

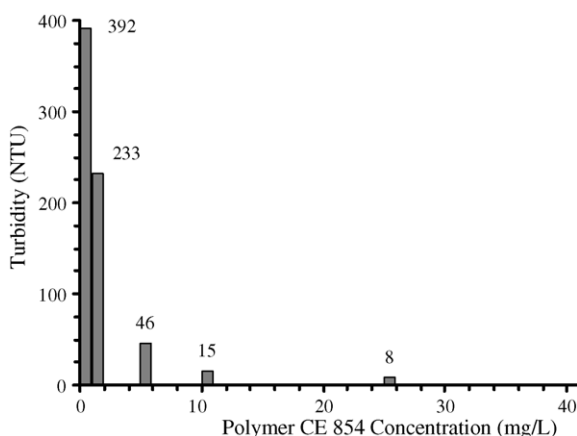


Fig. 2. The relationship between dosage concentration and turbidity for Hyperfloc CE 854, a polyacrylamide copolymer with a high degree of cationic charge and with a very high molecular weight.

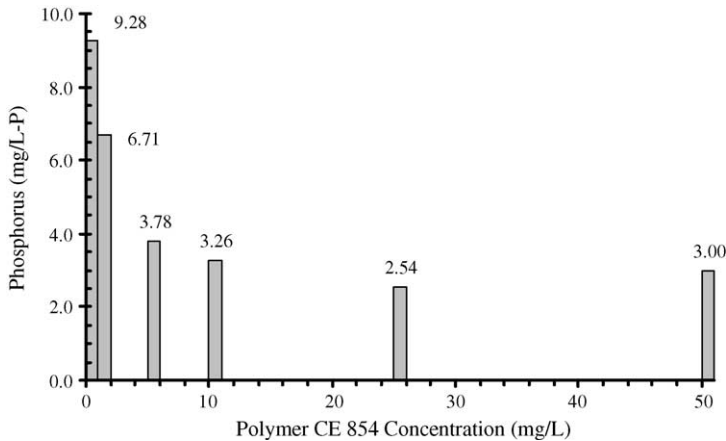


Fig. 3. The relationship between dosage concentration and Reactive Phosphorus for Hyperfloc CE 854, a polyacrylamide copolymer with a high degree of cationic charge and with a very high molecular weight.

2.1.4. Evaluation of selected polymers

Based on the results of the screening tests, six polymers were chosen for further study. Three of the polymers have a very high degree of cationic charge, two have a high degree of cationic charge, and one has a low degree of cationic charge. In addition, three have a very low molecular weight, one has a high molecular weight, and two have a very high molecular weight. No anionic charged polymers were chosen due to their low overall performance. Magnafloc LT 7991, 7992, and 7995 have a very high degree of cationic charge and a low molecular weight so should operate very similarly to coagulants alum and ferric chloride by adsorption-charge neutralization of particles. Hyperfloc CE 854 and CE 1950 have both a high degree of cationic charge and a high molecular weight and should provide both charge neutralization and bridging between particles. Magnafloc 22S with a very low degree of cationic charge and a high molecular weight should work primarily by bridging between particles.

Triplicate tests of these polymers were conducted over several weeks to try to obtain a wide range of backwash effluent water quality. In addition, to the other analysis, total suspended solids (TSS) was determined using standard methods (APHA, 1998). The impact of polymer dosage concentration is shown in Figs. 4–6 and a summary of results is shown in Tables 5 and 6 showing the removal efficiencies of TSS and RP from the raw microscreen waste discharge to the treated effluent at the optimal dosage level and also the impact of the polymer compared to settling alone.

Although a wide range of polymers were used, the results show excellent removal efficiencies for all of them, except for LT 22S. Total suspended solids removal was close to 99%, with final TSS values ranging from as low as 10 to 17 mg/L. Based on a single factor ANOVA test, there was a significant difference ($p < 0.001$) between the treatments. Post hoc pair wise comparison (Tukey) indicated that LT 22S was significantly different than all other treatments. There was no significant difference between any of the other treatments.

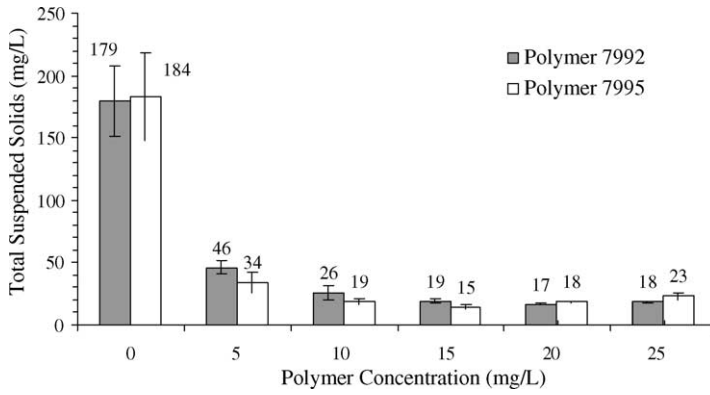


Fig. 4. Total suspended solids removed using very high degree of cationic charge, very low molecular weight polymer.

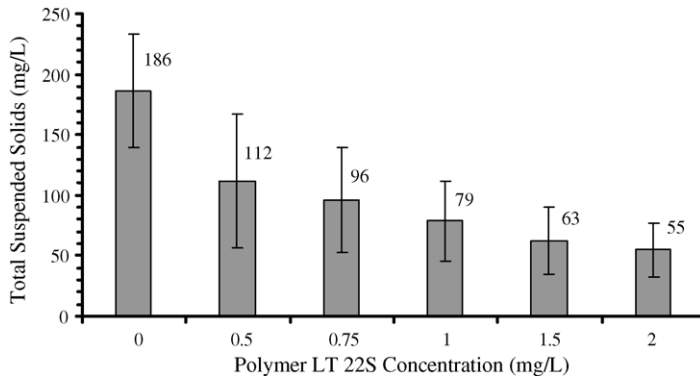


Fig. 5. Total suspended solids removed using low degree of cationic charge, high molecular weight polymer.

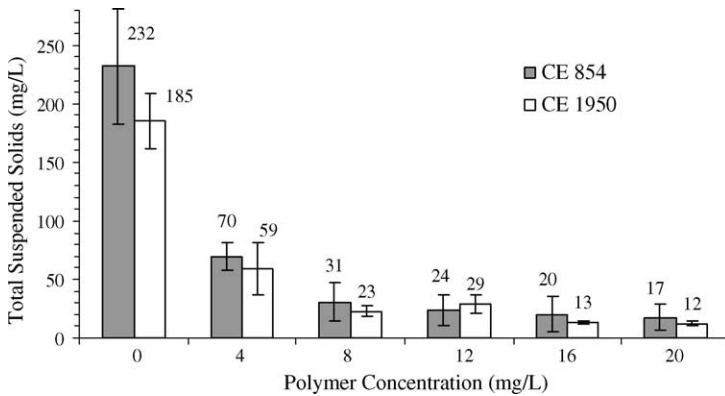


Fig. 6. Total suspended solids removed using high degree of cationic charge, very high molecular weight polymers.

Table 5

Removal efficiencies of TSS for settling alone, the impact of polymer over just settling, and overall removal efficiency

Polymer (optimal dosage ^a)	Raw TSS (mg/L)	Settled TSS (mg/L)	Treated effluent TSS (mg/L)	Removal settling only (%)	Additional removal with polymer	Removal settling and polymer (%)
LT 7991 (18)	825	219	19	73	91	98
	892	224	15	75	93	98
	773	164	15	79	91	98
Mean	830	202	16	76	92	98
S.D.	60	33	2.3	3	1	0.3
LT 7992 (20)	585	151	16	74	89	97
	1350	207	17	85	92	99
	1054	180	17	83	91	98
Mean	996	179	17	81	91	98
S.D.	386	28	0.6	6	1	1
LT 7995 (15)	982	224	17	77	92	98
	1231	168	14	86	92	99
	982	159	13	84	92	99
Mean	1065	184	15	82	92	99
S.D.	144	35	2.1	5	0.4	0.3
LT 22S (2)	1124	138	36	88	74	97
	1033	246	76	76	69	93
	1057	174	53	84	70	95
Mean	1071	186	55	82	71	95
S.D.	47	55	20	6	3	2
CE 854 (20)	1007	285	13	72	95	99
	843	188	9	78	95	99
	1046	224	9	79	96	99
Mean	965	232	10	76	96	99
S.D.	108	49	2	4	0.4	0.2
CE 1950 (20)	1100	159	17	86	89	98
	606	203	11	67	95	98
	806	194	12	76	94	99
Mean	837	185	13	76	93	98
S.D.	248	23	3	10	3	0.2

^a mg/L.

Although not intended to be used for RP removal, RP was reduced by 92–95% by removing most of the TSS in the wastewater to approximately 1 mg/L–P. Dosage requirements were fairly uniform, requiring between 15 and 20 mg/L of polymer. Although LT 22S did not show as good a removal efficiency as the others, 95% of TSS and 92% RP, the requirement of only 2 mg/L of polymer needs to be taken in consideration, in relationship to final discharge limits required.

Table 6

Removal efficiencies of RP for settling alone, the impact of polymer over just settling, and overall removal efficiency

Polymer (optimal dosage ^a)	Raw TSS (mg/L)	Settled TSS (mg/L)	Treated effluent TSS (mg/L)	Removal settling only (%)	Additional removal with polymer	Removal settling and polymer (%)
LT 7991 (18)	12.5	3.81	0.93	70	76	93
	18.0	4.85	1.24	73	74	93
	12.1	3.26	0.98	73	70	92
Mean	14	4.0	1.05	72	73	93
S.D.	3.3	0.8	0.17	2	3	1
LT 7992 (20)	9.0	2.5	0.79	72	68	91
	20.9	3.91	1.09	81	72	95
	19.2	4.1	0.91	79	78	95
Mean	16	3.5	0.93	77	73	94
S.D.	6.4	0.9	0.15	5	5	2
LT 7995 (15)	20.8	4.92	1.38	76	72	93
	27.4	3.71	0.97	86	74	96
	23.8	3.78	0.91	84	76	96
Mean	24.0	4.1	1.09	82	74	95
S.D.	3.3	0.7	0.26	5	2	2
LT 22S (2)	16.3	2.51	0.87	85	65	95
	18.9	5.02	1.69	73	66	91
	18.9	3.45	1.58	82	54	92
Mean	18.0	3.7	1.38	80	62	92
S.D.	1.5	1.3	0.45	6	7	2
CE 854 (20)	13.8	4.36	1.04	68	76	92
	16.0	4.30	0.83	73	81	95
	20.6	4.66	0.89	77	81	96
Mean	16.8	4.4	0.92	73	79	95
S.D.	3.5	0.2	0.11	4	3	2
CE 1950 (20)	21.1	3.55	0.90	83	75	96
	12.5	4.43	0.81	65	82	94
	15.4	4.07	0.89	74	78	94
Mean	16.3	4.0	0.87	74	78	95
S.D.	4.4	0.4	0.05	9	4	1

^a mg/L.

Tables 5 and 6 show the removal efficiencies for TSS and RP for settling alone and also the improvement over settling alone by using a polymer addition. It is interesting to note, that settling alone can remove from 76 to 82% of the TSS and from 72 to 82% of the RP under jar test conditions, confirming the results of Cripps and Bergheim (2000), who reported 30–84% of the phosphorus discharged from aquaculture systems is contained in

Table 7

Estimated costs to treat 1 metric tonne of feed, assuming 30% of the feed ends up as suspended solids and backwash water is 1000 mg/L TSS

Polymer	Cost of polymers/450 lb drum	Cost per kg	Cost per metric tonne of feed
LT 7991	\$247.50	\$1.21	\$7.26
LT 7992	\$148.50/450 lb drum	\$0.73	\$4.38
LT 7995	\$252.00/450 lb drum	\$1.23	\$7.38
CE 854	\$418.50/450 lb drum	\$2.05	\$13.08
CE 1950	\$418.50/450 lb drum	\$2.05	\$13.08

the solids fraction. The use of polymers improved the removal efficiencies substantially, removing from 71 to 96% of the remaining TSS and from 62 to 79% of the remaining RP.

The economics of using polymers look exceedingly good. Assuming that approximately 30% of the feed ends up as suspended solids in the waste stream and that the TSS concentration of the backwash water from the microscreen filter is approximately 1000 mg/L (1 g/L), then each kilogram of feed generates about 300 L of backwash water. Assuming a treatment of 20 mg/L on average, yields a polymer requirement of only 6 g per kg feed. Costs of the polymers were obtained from two manufacturers and are listed in Table 7. One of the problems with industrial chemicals is that they are usually available only in large quantities, so the smallest size for Ciba Specialty Chemicals is a 450 lb drum and the next size is a 2400 lb tote bin. The smallest quantity available from Hychem is a 5 gal pail, next a 450 lb drum, a non-returnable tote 2300 lb (275 gal) and finally the largest quantity available is a railroad tanker. As can be seen from Table 7, the overall operating cost for the polymers investigated is very small in comparison to the cost of the feed.

3. Conclusions

The results of this preliminary evaluation of a broad range of polymers showed that there is no one type of polymer flocculant, either by chemical family, ionic charge, or molecular weight, that predicts the performance as a flocculation aid. The best performing polymer is best determined by industrial recommendations, experience and laboratory and field testing. Results of these evaluations show TSS removal was close to 99%, with final TSS values ranging from as low as 10–17 mg/L. These results are based on jar test and ‘real world’ settling basins performance may differ due to non-ideal conditions. Although not intended to be used for RP removal, RP was reduced by 92–95% by removing most of the TSS in the wastewater. Dosage requirements were fairly uniform, requiring between 15 and 20 mg/L of polymer. At this time, additional testing is planned for the polymers that showed significant impact on suspended solids. These would include optimizing-mixing and flocculation speeds and duration and dosages. Limited economic data was obtained from the manufacturers and polymer cost per kg of feed was estimated. These costs range from \$4.38 per metric tonne of feed for LT 7992 to \$7.30 per metric tonne for LT 7991 and LT 7995 to \$13.08 per metric tonne of feed for CE 854 and CE 1950.

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