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Coagulation/flocculation of beet sugar wastewater

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The wastewater of the Centrale Suiker Maatschappij (CSM) sugar company at Vierverlaten, Groningen, the Netherlands, consists mainly of water used for hydraulic transportation or "fluming" of sugar beets. Fluming is possible because sugar beets have almost the same density as water; thus the beets are readily carried along by a moving stream.

This means of transportation is not only effective and easy, but also washes away dirt encrusted on the beets. However, it has one disadvantage: some sugar is lost to the flume water by diffusion through the skin of the beet, or, more seriously, from broken beets.[1] In addition to dirt and sugar, the wastewater (total flow of 35 m^3/min) contains other sugar products and excess condensate with a large amount of ammonia (Figure 1). The larger particles are settled in a sedimentation tank; the remaining liquor is cooled and treated in an aerated lagoon. The water is recirculated into the mill; only a portion is discharged. This study investigated coagulation/flocculation of the effluent from the aerated lagoon as a method to permit reuse of this effluent in the sugar mill, or, alternatively, to permit discharge to surface waters.

The following investigations were performed:

- Jar tests with three inorganic coagulants to establish their required doses, pH ranges, and the possible use of coagulation aids;
- Comparison of batch experiments with continuous-flow laboratory experiments and pilot-plant studies; and
- Determination of some design criteria of a coagulation/flocculation plant for sugar mill wastewater.

EXPERIMENTAL SET-UP

Experiments were performed in three ways: on a batch scale, in a laboratory-scale pilot plant, and in a 6-m^3/h pilot plant. The batch coagulation/flocculation tests were done in rectangular 2-l plexiglass tanks with a cross-sectional area of 10 × 10 cm^2. The following test procedure was used:

- Mixing with a turbine stirrer at 660 rev/min, which gave a G-value of about 680/s, measured by means of a torque meter;
- Addition of coagulant solution and then pH-adjustment over a 60-second period at 660 rev/min (rapid mix);
- Flocculation for 30 minutes with a propeller-type stirrer at 67 rev/min (G = 28/s); and
- Sedimentation for 30 minutes.

After sedimentation, a sample of about 100 ml was taken at the half-height of the tank and the sludge volume was measured.

The laboratory-scale flocculator (Figure 2) had a flow of 0.06 m^3/h and consisted of a rapid-mix vessel for coagulant feed and pH-adjustment. This vessel had a volume of 1 litre and was stirred with a turbine-type stirrer at 365 rev/min, which gave a G-value of 150/s. After this initial mixing, the wastewater entered a four-reactor plug-flow flocculator, with a total volume of 20 l. The pH electrode was placed in the first flocculation compartment. The reactors were stirred by a flat-blade stirrer at 63, 50, 22, and 10 rev/min. For technical reasons, the G values were measured at the end of the experimental period; they amounted to 60, 32, 14, and 5/s. Finally the wastewater was allowed to settle in a Dortmund-type sedimentation tank, from which the settled sludge was drawn off con-

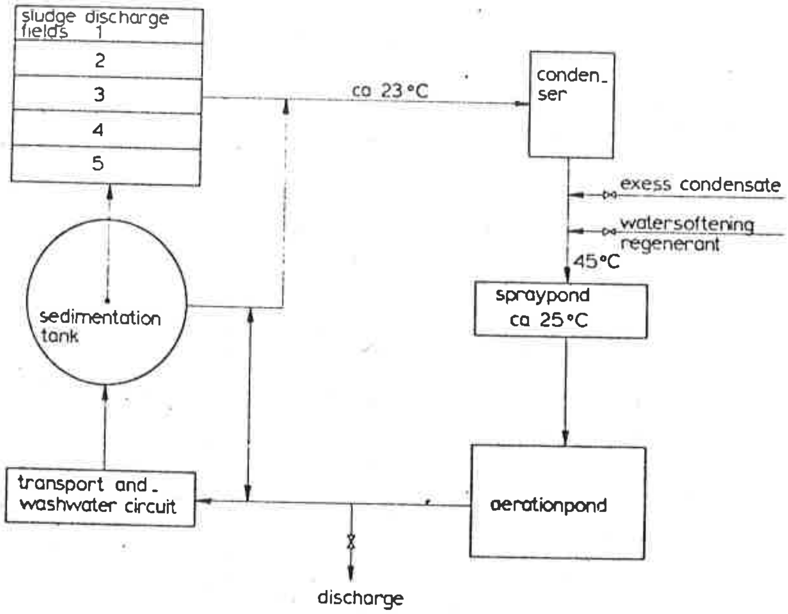

FIGURE 1. Simplified water flow diagram of the sugar mill.

tinuously. The detention time in the tank was 1 hour; the surface loading rate was 0.5 $m^3/m^2 \cdot h$.

The second pilot plant was a circulator-type (Degrémont Holland B. V.) sludge blanket flocculator. In the circulator (Figure 3) wastewater and coagulant are mixed initially in the influent pipe. Flocculation occurs in a conical pipe inside the tank. Polyelectrolytes are added at the overflow of the conical pipe. Flocculation time is governed by influent flow, which ranged from 4 to 8 m^3/h. The volume of the circulator was 5 m^3, and the surface loading was also determined by the wastewater flow according to the following:

Wastewater flow (m^3/h)	Surface loading ($m^3/m^2 \cdot h$)	Detention time (h)
4	2.2	1.25
5	2.7	1.00
6	3.3	0.83
7	3.8	0.71
8	4.4	0.63

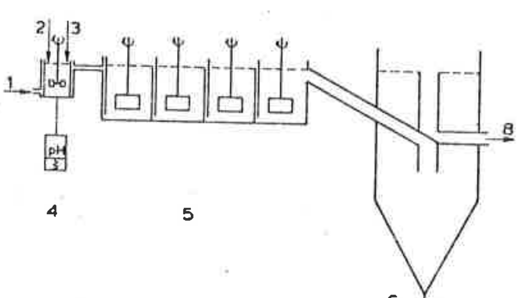

FIGURE 2. The laboratory-scale pilot plant (60 l/h): 1. influent, 2. coagulant dosage, 3. pH adjustment, 4. mixing vessel, 5. flocculator, 6. sedimentation tank, 7. sludge discharge, 8. effluent.

To estimate the settling velocity of the sludge floc, some experiments were carried out in a settling cylinder, with sampling points at different heights. The volume of this cylinder was 0.2 m^3 and the diameter was 0.30 m.

Ferric chloride (40% w/w solution), aluminium sulfate [$Al_2(SO_4)_3 \cdot 18H_2O$] and hydrated lime [$Ca(OH)_2$], were used as coagulants. An anionic, a nonionic, and a cationic synthetic polymer (American Cyanamid Co., Superfloc A100, N100, and C100, respectively) were used as coagulant aids.

RESULTS

Batch experiments. Batch experiments were carried out to determine the ratio of coagulant dose to flocculation effect, the optimal flocculation pH, the effect of addition of coagulant aids, and the amount of sludge produced.

An illustration of the results obtained with ferric chloride in batch experiments is given in Table I. In this table the chemical oxygen demand of the total sample (COD_t) and the

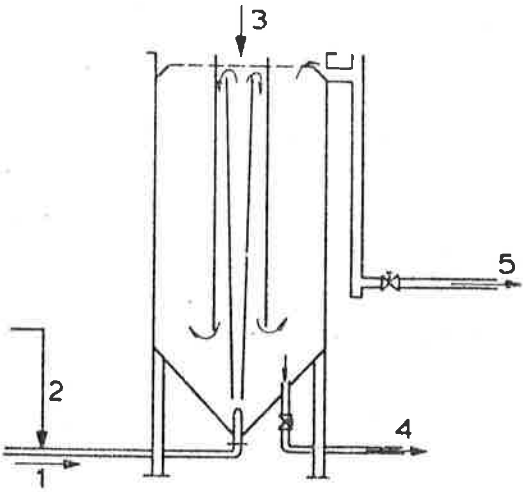

FIGURE 3. The sludge blanket flocculator (4 to 8 m^3/h): 1. influent, 2. coagulant dosage, 3. coagulant aid dosage, 4. sludge discharge, 5. effluent.

COD of the supernatant after centrifuging at about 2 500 g for 15 minutes (COD_c) are given with the percentage COD_t reduction at various coagulant doses.

At the start of the working season, the alkalinity of the wastewater was relatively low. During this period, coagulation/flocculation was performed at a pH of at least 5.0 to prevent flotation of flocs by carbon dioxide. Within a few weeks, the alkalinity of the wastewater was so high (about 20 meq HCO_3^-/l) that even at ferric chloride doses up to 250 mg Fe/l, no pH decrease below 5.0 was observed.

TABLE I. Different ferric chloride doses at different pH values (batch experiments).[a]

Coagulant Dose (mg Fe/l)	pH	COD_t Reduction (%)	Sludge/ Wastewater (% by-volume)
50	5.5	30	15.0
100	5.5	55	20.0
150	5.5	67	30.0
200	5.5	75	32.0
250	5.5	85	32.0
100	4.0	47	25.0
100	5.0	57	20.0
100	6.0	54	23.0
100	7.0	54	25.0

[a] pH wastewater = 7.8, COD_t wastewater = 1 280 mg O_2/l, and COD_c wastewater = 425 mg O_2/l.

TABLE II. Effect of coagulant aid on COD reduction and sludge volume for coagulation/flocculation with ferric chloride.[a]

Coagulant Dose (mg Fe/l)	Coagulant Aid Dose (mg/l A100)	COD_t Reduction (%)	Sludge/ Wastewater (% by volume)
100	—	60	13.5
100	1.0	60	10.5
100	1.5	65	10.0
100	2.0	64	10.0
100	2.5	67	12.5
100	3.0	66	—

[a] pH wastewater = 7.3, pH coagulation = 5.5, COD_t wastewater = 1 010 mg O_2/l, and COD_c wastewater = 500 mg O_2/l.

It turned out that pH had little effect on COD removal in a pH range from 5.0 to 7.0. Table I shows that, depending on the coagulant dose, up to 85% COD_t elimination can be achieved. The experiments showed that the addition of 1 to 2 mg/l anionic polymer A100 with ferric chloride results in an extra COD reduction of about 5% and a reduction of the volume of sludge produced (Table II). The addition of a cationic or a nonionic polymer as coagulant aid had a negligible effect. Several experiments showed that COD removal was maximal when more than 200 mg Fe/l was added.

When alum [$Al_2(SO_4)_3 \cdot 18H_2O$] was used as coagulant, batch experiments showed that the optimal pH for coagulation/flocculation was also higher than 5.0. Table III illustrates that the maximal COD reduction of about 92% occurred at doses higher than 100 mg Al/l. Considerable amounts of sludge were produced. This sludge volume could be reduced by adding 1 to 2 mg/l nonionic polymer N100 as coagulant aid, while anionic and cationic polymers were not so effective (Table IV). Previous coagulation/flocculation experiments with wastewater of domestic origin (Leentvaar *et al.*,[2] Minton and Carlson[3]) showed that, with hydrated lime as a coagulant, the coagulation/flocculation process is determined by the pH, with the understanding that COD removal increases with rising pH. The coagulant can be dosed either up to a fixed pH (for example, pH 11.2) or with a fixed dose. The amount of hydrated lime required for coagulation/flocculation depends on the alkalinity and hardness of the water treated. The experiments with sugar-beet

TABLE III. Different doses of alum at different pH values (batch experiments).[a]

Coagulant Dose (mg Al/l)	pH	COD_t Reduction (%)	Sludge/ Wastewater (% by volume)
30	5.5	37	4.5
60	5.5	75	17.5
120	5.5	88	37.0
150	5.5	90	42.5
180	5.5	92	50.5
210	5.5	91	57.5
240	5.5	91	66.0
270	5.5	91	80.0
300	5.5	92	85.0
90	4.0	79	10.0
90	5.0	86	25.0
90	6.0	84	27.5
90	7.0	82	24.5

[a] pH wastewater = 7.9, COD_t wastewater = 1 400 mg O_2/l, and COD_c wastewater = 425 mg O_2/l.

wastewater, however, showed (Table V) that pH was not the most important factor in this coagulation/flocculation process. A fixed amount of hydrated lime added to the wastewater gave a higher COD removal percentage, up to 79%, than when a lime dose was added to a fixed pH. This is possibly a result of the low alkalinity of the wastewater at the start of the working season of the sugar mill; therefore, the lime dose per unit volume of wastewater was fixed. Table V shows that COD removal was maximal at lime doses above 2 500 mg $Ca(OH)_2$/l. The addition of organic polymers together with lime had almost no effect on the

TABLE IV. Effect of a nonionic polymer on COD reduction and sludge volume for coagulation/flocculation with alum in batch.[a]

Coagulant Dose (mg Al/l)	Coagulant Aid Dose (mg/l N100)	COD_t Reduction (%)	Sludge/ Wastewater (% by volume)
100	—	78	58.0
100	1.0	70	51.0
100	2.0	70	36.5
100	3.0	76	30.0
100	4.0	71	26.0
100	5.0	79	26.0

[a] pH wastewater = 7.8, pH coagulation = 5.5, COD_t wastewater = 1 300 mg O_2/l, and COD_c wastewater = 330 mg O_2/l.

TABLE V. Hydrated lime as coagulant from batch experiments.[a]

Coagulant Dose [mg $Ca(OH)_2$/l]	pH	COD_t Reduction (%)	Sludge/ Wastewater (% by volume)
660	9.6	7	—
1 320	11.5	23	4.5
1 980	11.8	54	5.5
2 640	12.0	62	6.0
3 300	12.0	72	9.5
3 960	12.1	75	10.0
4 620	12.0	78	12.0
5 280	12.1	75	12.0
5 940	12.2	75	12.5
6 600	12.2	79	12.0

[a] pH wastewater = 7.6, COD_t wastewater = 1 240 mg O_2/l, and COD_c wastewater = 590 mg O_2/l.

COD removal and volume of the produced sludge. Addition of small quantities of ferric chloride (about 10 mg Fe/l) with the lime led to a substantial improvement in COD removal, but also to an increase in sludge volume.

A disadvantage of lime treatment is the high effluent pH and the increase in the hardness of the treated water. The hardness of the raw wastewater averaged 7.6 meq/l; depending on the lime dose [1 500 to 3 000 mg $Ca(OH)_2$/l], the effluent hardness ranged from 20.5 to 40.3 meq/l. This effluent was thus unfit for recirculation in the sugar mill. However, these disadvantages could be prevented by recarbonation.

As nitrogen plays an important role in the discharge cost for polluted waters into surface water or into the local sewer system, the elimination of organic and inorganic nitrogen compounds was examined incidentally both in batch experiments and in the two pilot plants. All data showed a linear relationship (Figure 4) between COD and Kjeldahl nitrogen removal (Number of data = 17; correlation coefficient $r = 0.88$).

Table VI lists reductions for COD, total organic carbon (TOC), and volatile organic acids by coagulation/flocculation with different doses of ferric chloride, alum, and hydrated lime. The amounts of acetic, propionic, isobutyric, butyric, isovaleric, and valeric acids were determined. The last three compounds played relatively minor roles (concentrations less than 5 mg/l). Table VI shows that volatile organic acids were not removed by coagulation/

TABLE VI. COD and TOC values and the concentration of volatile organic acids after coagulation/flocculation in a batch experiment (7.5 pH wastewater).

Coagulant	Coagulant Dose (mg/l)	COD (mg O_2/l)	TOC (mg C/l)	Volatile Organic Acids[a]		
				C_2 (mg/l)	C_3 (mg/l)	iC_4 (mg/l)
Wastewater		4 610	1 230	250	400	5
Fe	50	3 960	1 070	270	420	5
	150	2 120	595	295	465	7
	250	1 210	450	290	460	4
Al	30	3 640	1 135	250	405	5
	90	1 690	505	315	500	6
	150	1 400	465	280	440	5
$Ca(OH)_2$	1 000	3 670	1 030	310	470	5
	2 000	2 830	920	310	485	6
	3 000	2 160	635	253	410	6

[a] C_2 = acetic acid, C_3 = propionic acid, and iC_4 = isobutyric acid. C_4, iC_5, and C_6 components < 5 mg/l.

flocculation—in fact, the concentration of these acids increased during the treatment. The removal percentage based on COD was somewhat higher than the removal percentage based on TOC.

The wastewater of the beet-sugar mill does not have a constant quality. During the working season, the total COD and the supernatant COD after centrifuging at about 2 500 g (COD_c) increased (Figure 5). This COD_c comes from soluble products such as sugars and volatile organic acids and also some colloidal material. It was assumed that the increasing wastewater COD during the working season decreases the COD removal percentage at a fixed coagulant dose. Batch experiments with the three coagulants at fixed coagulant doses, however, showed a constant removal efficiency with respect to COD. The COD_t removal decreased when there was an extra increase in COD_c after a process failure. This extra supply of molasses (COD_c) decreased the COD_t removal because this soluble product was not involved in coagulation (Table VII).

Pilot-plant experiments. As mentioned previously, two continuous-flow pilot plants were used: a laboratory-scale plant with a wastewater flow of 0.06 m³/h and a circulator with a flow adjustable from 4 to 8 m³/h. The experiments with the laboratory pilot plant were

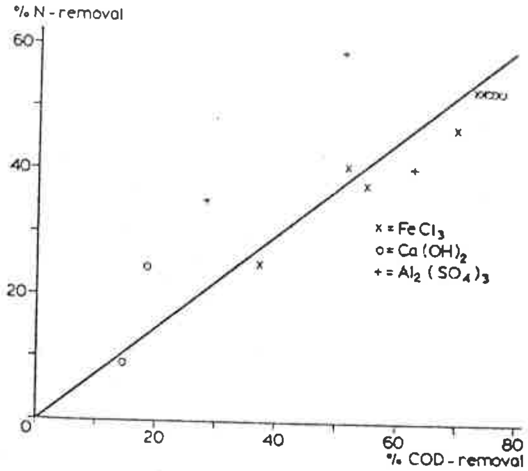

FIGURE 4. The relation between COD removal and nitrogen removal with different coagulants used.

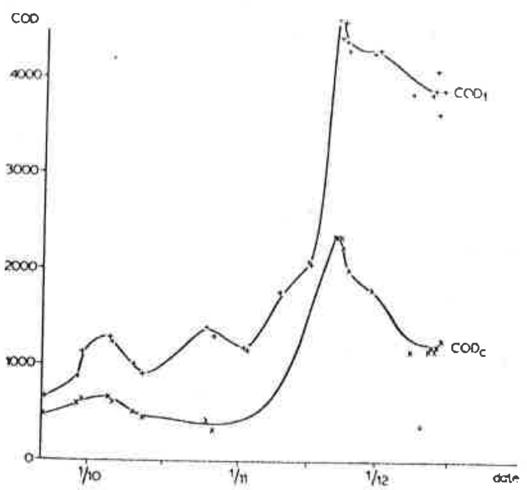

FIGURE 5. COD_t and COD_c of the wastewater during the working season.

TABLE VII. COD reduction before and after the extra supply of molasses to the wastewater.

Coagulant	Coagulant Dose (mg/l)	COD_t reduction percentage Before	After
Fe	50	38	15
	100	60	—
	150	70	51
	250	80	72
Al	30	36	22
	60	75	44
	90	84	64
	150	90	70
$Ca(OH)_2$	1 000	23	12
	2 000	65	31
	3 000	73	47

to determine whether the COD removal percentages of the jar test corresponded with those of the continuous experiments. For this reason, the surface loading of the sedimentation tank was very low: 0.5 $m^3/m^2 \cdot h$. Design criteria were obtained through experiments with the circulator, together with experiments in the sedimentation cylinder. For this reason, the surface loading and, by that, the average detention time of the liquid in the circulator were varied. The experiments were performed with large and small coagulant doses and with a coagulant aid. For coagulation/flocculation with ferric chloride as coagulant, 2.0 mg/l anionic polymer A100 was added; with alum, 2.0 mg/l nonionic polymer N100; and with hydrated lime, 30 mg/l Fe. A synopsis of data of the experiments on batch scale, laboratory scale, and semitechnical scale is given in Table VIII. Other experiments gave the same results.

Figure 6 illustrates that the removal percentages of both laboratory-scale flocculator and circulator corresponded well with those obtained in the jar tests for all three coagulants. The correlation coefficient (r) between the laboratory-scale data and the batch experiments data was 0.92 ($N = 17$) and that between the circulator experimental results

TABLE VIII. Synopsis of data of experiments on bath scale (B), laboratory scale (L), and semitechnical scale (C).[a]

Coagulant	Coagulant Dose (mg/l)	COD_t/COD_c (mg O_2/l)	COD_t Reduction (%) B	L	C	Surface Loading C (m/h)
Fe	50	1 180/495	38	56	39	2.7
	50	1 160/515	48	57	39	2.7
					37	3.8
	200	1 340/375	88	85	92	2.2
					80	3.3
Al	30	2 190/795	51	40	64	2.2
	30	2 070/665	47	45	64	2.2
	30	4 640/2 410	24	30	23	2.2
					28	2.7
	30	4 430/2 350	13	17	20	2.2
					21	3.8
	60	4 390/2 240	46	52	45	2.2
					37	3.8
	60	4 310/2 000	42	56	51	2.2
					28	3.8
	60	4 210/1 790	41	28	49	2.2
					52	3.3
	60	4 320/–	44	53	42	3.8
$Ca(OH)_2$	1 000	3 860/1 170	9	11	10	3.8
	1 000	3 910/1 200	12	11	10	3.8
	1 000	4 100/1 165	14	12	14	3.8
	2 000	3 640/1 200	20	16	24	3.8
	2 000	5 530/1 200	43	47	47	3.8
	2 000	3 890/1 270	25	19	19	4.5

[a] Coagulant aids: Fe, 2.0 mg A100/l; Al, 2.0 mg N100/l; and Ca, 30 mg Fe/l.

and the results of the jar tests was 0.93 ($N = 24$), in which N is the number of experiments.

Design. Because the cost of the sedimentation tank is the most important part of the investment cost, this tank should be designed very carefully. Therefore, the settling velocity of the flocs was measured under different conditions in a vertical settling cylinder, as previously described. The wastewater in the cylinder was flocculated by adding a large or small amount of coagulant together with a coagulant aid and by mixing with a perforated plate. During the settling of the flocs, samples were taken at different heights of the cylinder; from these the COD was determined. As flocculent particles settle, the settling velocity increases with time and depth. In the case of the sedimentation cylinder, efficiency of the sedimentation decreases with the height of the sampling point. An example is given in Figure 7 in which the removal ratio by sedimentation is given as a function of the surface loading for different depths of the sedimentation tank for the case of 1 000 mg $Ca(OH)_2$/l and 30 mg Fe/l as coagulant (aid).

From these graphs the surface loading of an upflow sedimentation tank with a known depth can be determined at a fixed degree of purification. These values are given in Table IX, which shows that a small coagulant dose led to some flocculent settling and that a high dose led to zone sedimentation (compare 30 and 90 mg Al/l).

Similar settling tests proved that an increase

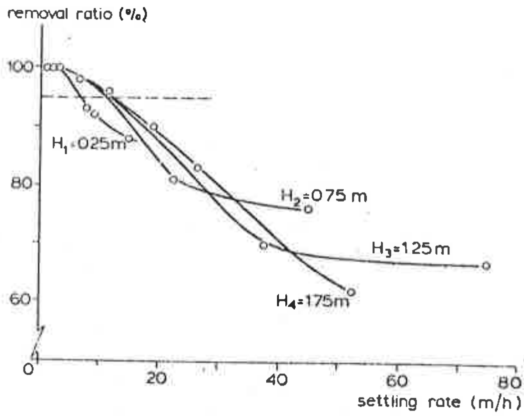

FIGURE 7. Removal ratio by sedimentation as a function of the surface loading/settling rate for different depths (H) of the sedimentation cylinder, for the case of 1 000 mg/l $Ca(OH)_2$ plus 30 mg/l Fe as coagulants.

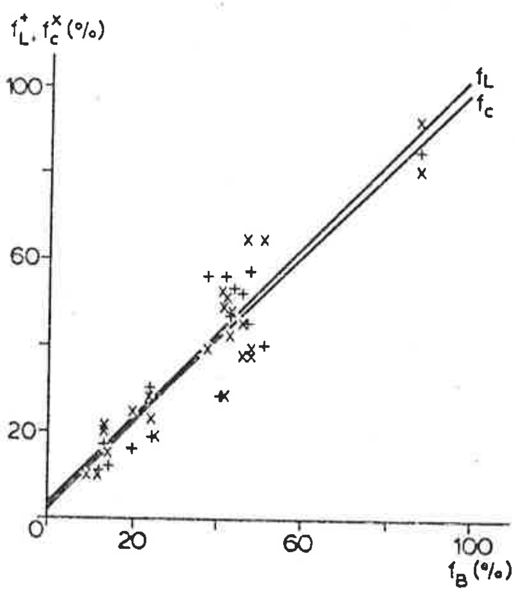

FIGURE 6. Relation between removal percentage of the batch experiments (f_B) and the removal percentage of the laboratory scale (f_L) and the pilot-plant scale (f_C) experiments, based on COD.

TABLE IX. Relation between settling rate (S) and depth of sedimentation tank (H) for different coagulants (removal ratio 95%).

Coagulant Dose	H (m)	S (m/h)
50 mg Fe/l + 2.0 mg A100/l	0.25	8.0
	0.75	8.5
	1.25	10.0
	1.75	8.5
200 mg Fe/l + 2.0 mg A100/l	0.25	0.6
	0.75	3.8
	1.25	4.3
30 mg Al/l + 2.0 mg N100/l	0.25	2.7
	0.75	3.3
	1.25	4.1
	1.75	4.1
90 mg Al/l + 2.0 mg N100/l	0.25	1.4
	0.75	1.6
	1.25	1.7
1 000 mg $Ca(OH)_2$/l + 30 mg Fe/l	0.25	6.5
	0.75	12.0
	1.25	13.0
	1.75	13.0
2 000 mg $Ca(OH)_2$/l + 30 mg Fe/l	0.75	2.4
	1.25	3.2
	1.75	<4.2

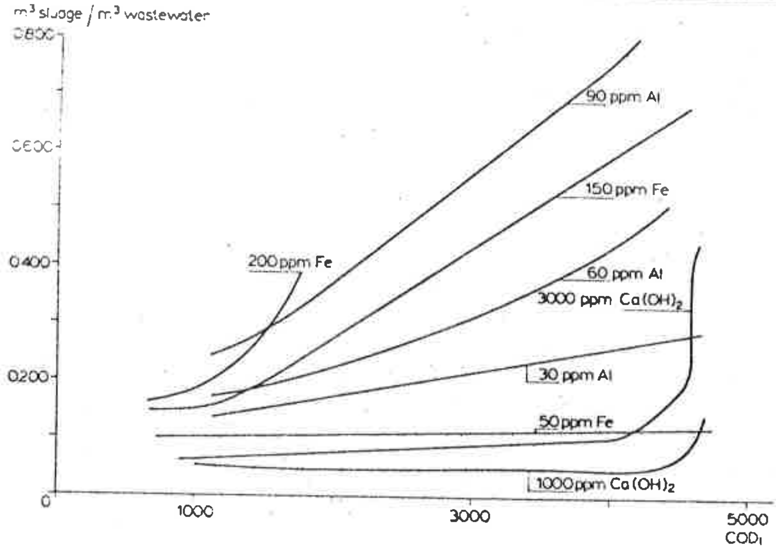

FIGURE 8. Volume sludge produced per m³ wastewater as a function of wastewater COD and type of coagulant.

of suspended solids in the wastewater had a positive effect on the settling rate: hence a settling rate that is lower at the start of the working season than at the end of the season. The tests also showed that addition of coagulant aids resulted in larger flocs, which settle more rapidly. The results of the tests in the sedimentation cylinder agreed reasonably well with those obtained with the circulator, as illustrated in Table VIII, which shows that in the case of coagulation with 60 mg Al/l, a surface loading of 3.8 m/h was too high for adequate separation of the flocs and the effluent; flocs appeared in the effluent, and the COD removal percentage decreased.

This result corresponded with those of the column settling test (Table IX) at a dose of 90 mg Al/l, in which the settling velocity at a depth of 1.25 m was 1.7 m/h; if the values for the settling velocity at 0.25, 0.75, and 1.25 m are extrapolated, then the sedimentation rate will not be 3.8 m/h or higher at a depth of 3.5 m in the circulator.

Sludge. As illustrated in Figure 8, the amount of sludge produced depends on the COD of the wastewater and the dose and kind of coagulant. The dry solids content of the sludge was 10 g/l with ferric cloride and alum as coagulant and 25 to 30 g/l with coagulation/flocculation by hydrated lime. The volume of the sludge and its dry solids content was measured after 30 minutes of sedimentation. Addition of coagulant aids and sludge recirculation will have a positive effect on the dry solids content of the sludge.

The sludge produced in the physico-chemical treatment has to be transported for about 450 m to be dumped together with solid material from the sugar production on a wastewater field. A jar test was set up to gain an impression of the strength of the sludge floc. Sugar-waste sludge, physico-chemical sludge, and a 5:1 mixture of both sludges was agitated with a velocity gradient of about 200/s for 3 minutes. After 24 hours the COD_t values of the supernatant and the sludge volume were measured and compared with these values before agitation. Table X shows that the agitation of iron sludge led to a 22% increase in COD and also to an increase in the volume of sludge. Alum and lime sludges were very strongly disintegrated by agitation. Agitation of a 5:1 mixture of sugar-waste sludge with iron or lime sludge resulted in an increase of the COD of the supernatant by about 22% and a decrease in sludge volume of 14%.

Agitation of sugar-waste sludge gave an increase in the COD of the supernatant by 5%. As the flow of suspended sugar-waste sludge was 480 m³/h and the flow of the physico-chemical sludge was in practice 20 m³/h, the COD percentage increase as a result of the agitation/transportation of this mixture would be less than 5% if the agitation were not higher than 200/s. The G value of 200/s corresponds

TABLE X. Influence of agitation on the release of COD from physico-chemical sludge and sugar waste sludge.[a]

Sludge Type	COD_t Supernatant			Sludge/wastewater (% by volume)		
	Before Agitation (mg O_2/l)	After Agitation (mg O_2/l)	Difference (%)	Before Agitation	After Agitation	Difference (%)
Sugar waste sludge	4 650	4 890	(+ 5)	14.0	14.5	(+ 4)
Iron sludge	2 020	2 460	(+ 22)	42.0	46.5	(+11)
Mixture (Fe)	4 400	5 320	(+ 21)	17.5	15.0	(−14)
Alum sludge	2 310	4 900	(+112)	41.0	34.0	(−17)
Mixture (Al)	4 530	6 169	(+ 36)	14.5	12.5	(−14)
Lime sludge	3 680	9 880	(+168)	50.0	42.5	(−15)
Mixture (Ca)	4 660	5 790	(+ 24)	17.5	15.0	(−14)

[a] The COD of the supernatant was measured after 24 hours of sedimentation. The "mixture sludge" consisted of a 5:1 mixture of sugar-waste sludge and physico-chemical sludge.

roughly with a pipe diameter of 0.15 m at a flow of 20 m³/h.

ECONOMIC ASPECTS

Though the capital cost of a physico-chemical wastewater treatment plant is lower than that of a mechanical/biological plant, the recurring costs of physico-chemical plant are in most cases higher. The recurring costs of the coagulation/flocculation step consist mainly of the cost of the coagulants. The cost given in Table XI for the various doses of coagulant were calculated using the following prices: ferric chloride (40% w/w $FeCl_3$ solution)—\$103.85/metric ton, alum (98% $Al_2(SO_4)_3 \cdot 18\,H_2O$)—\$162.27/metric ton, and lime [98% $Ca(OH)_2$]—\$85.26/metric ton.

Coagulant efficiency is defined as the total

TABLE XI. A survey of the coagulant efficiency and the coagulant cost at different wastewater COD and with different coagulants.

Coagulant	Coagulant Dose (mg/l)	Wastewater COD_t (mg O_2/l)	Coagulant Efficiency (kg COD removed/ kg coagulant)	Coagulant Cost/ kg COD Removed (f)
Fe	50	<1 000	4.0– 7.5	0.18–0.34
	50	>2 000	14.0–15.0	0.09–0.10
	100	<1 000	4.0– 6.0	0.23–0.34
	200	<1 000	2.7– 3.6	0.38–0.51
	200	1 000–2 000	3.6– 8.0	0.17–0.38
	250	<1 000	2.5– 3.0	0.46–0.55
	250	>2 000	~13	~0.11
Al	30	<1 000	~15	~0.25
	30	>2 000	15.0–45.0	0.08–0.25
	60	<1 000	~15	~0.25
	60	>2 000	15.0–40.0	0.09–0.25
	90	<1 000	~11	~0.34
	90	>2 000	11.0–25.0	0.15–0.34
	150	<1 000	~7.5	~0.50
	150	>2 000	7.5–20.0	0.19–0.50
$Ca(OH)_2$	1 000	<1 000	~0.4	~0.39
	1 000	>2 000	0.3– 1.0	0.16–0.52
	2 000	<1 000	~0.35	~0.44
	2 000	>2 000	0.6– 1.0	0.16–0.26
	3 000	<1 000	~0.25	~0.26
	3 000	>2 000	0.5– 0.7	0.22–0.31

amount of COD removed per unit coagulant expressed as kg COD/kg coagulant. Table XI surveys coagulant efficiency and coagulant cost of the three coagulants used in this study. This table illustrates that at a certain coagulant dose, coagulant efficiency increases with rising wastewater COD. At a given wastewater COD, the coagulant efficiency decreased with rising coagulant doses after a certain point.

In view of the coagulant cost, the following coagulant dose is recommended: 50 to 100 mg Fe/l, 30 to 60 mg Al/l, or 1 500 to 2 000 mg $Ca(OH)_2$/l. The choice of the coagulant dose at equal cost per kg COD removed depends on the desired effluent quality and/or the sludge handling and disposal facilities.

DISCUSSION

After sedimentation and aeration, the wastewater of the CSM sugar mill Vierverlaten can be coagulated and flocculated easily under normal conditions by any of the three coagulants, ferric chloride, alum, or hydrated lime. The degree of purification depends partly on the ratio of total COD to COD of the supernatant after centrifuging and on the kind and dose of the coagulant. The addition of coagulant aids such as A100 with ferric chloride as coagulant and N100 with alum as coagulant has a positive effect on COD removal, on the settling rate of the flocs produced, and on the volume of the sludge produced.

To minimize the volume of sludge produced, the coagulant dose should not be too large. The experiments proved that batch coagulation/flocculation tests in rectangular tanks can describe the continuous flow experiments very well and are very useful for estimating the coagulation/flocculation process in practice, for surveying the coagulation/flocculation plant, and for determining the optimal coagulant feed. The settling rate of the flocs as determined with the vertical sedimentation tube give a good indication of the surface loading of the vertical flow settling tank that can be applied. The disadvantage of using alum as coagulant is the possibility of sulfate reduction coupled with release of H_2S when the oxygen supply is insufficient. The disadvantage of hydrated lime as coagulant is the high effluent pH together with the severe hardness of the treated water. With respect to the coagulant cost per kg COD removed, the use of ferric chloride as coagulant, especially with small doses, is the most favorable. The settling rate of the flocs with small ferric chloride doses is also favorable.

The successful application of a coagulation/flocculation system also depends on the kind of biological wastewater treatment applied, because the coagulation/flocculation process removes mainly suspended and colloidal material, while soluble, easily biodegradable compounds remain in solution. Recent experiments have shown that coagulation/flocculation, especially in combination with anaerobic biological pretreatment of wastewater, can be successful.[4]

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REFERENCES

1. McGinns, R. A., "Beet-Sugar Technology." Reinhold Publ. Corp., New York, N. Y. (1951).
2. Leentvaar, J., *et al.*, Physico-Chemical Treatment of Municipal Wastewater—Coagulation-Flocculation." *Water Res.*, 12, 35 (1978).
3. Minton, G. R., and Carlson, D. A., "Primary Sludges Produced by the Addition of Lime to Raw Wastewater." *Water Res.*, 7, 1821 (1973).
4. Lettinga, G., *et al.*, "Anaerobe Treatment of Beet-Sugar Factory Wastewater in a 6 m³ Pilot Plant (Dutch)." *H_2O*, 10, 526 (1977).