PAPERMAKING CHEMISTRY

PEER REVIEWED

Optimizing flocculation and drainage for microparticle systems by controlling zeta potential

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ABSTRACT

A laboratory system has been developed to measure simultaneously the zeta potential, flocculation, and drainage of pulp and filler suspensions under hydrodynamic shear flow. This instrument was used to optimize flocculation and drainage for single polymer systems and microparticle systems. Flocculation and drainage were affected by the order of chemical addition, the types of chemicals, and the type of furnish. Drainage increases that occurred with the addition of bentonite were strongly influenced by charge neutralization.

Application:

This study can help increase the speed of a paper machine.

IT STARTED IN EUROPE, WHERE natural ground calcium carbonate of high quality is abundant *(1)*. The conversion to alkaline papermaking has taken root in North America as well, where many on-site plants are now producing precipitated calcium carbonate (PCC) *(2)*. The primary economic benefit is that furnish costs are lower because the high-brightness calcium carbonate fillers are relatively inexpensive.

In acid papermaking, alum can effectively treat groundwood white water, which is a reservoir for anion trash, pitch, and by-products of the bleaching process. In alkaline papermaking, however, alum cannot be used because calcium carbonate dissolves below pH 7 and would go back into solution. In addition, the PCC fillers cause slower drainage, and mechanical pulp fines make it more difficult to achieve good dewatering and high retention.

Our overall objective is to improve flocculation and drainage in alkaline papermaking. Our scope covers flocculation and drainage for groundwood-free and groundwood-containing furnishes that are meant to retain a single polymer or meant for microparticle retention aid systems. In the work reported here, we used on-line monitoring instruments to measure the zeta potential, flocculation, and drainage of the pulp and fillers under conditions of hydrodynamic shear. In doing so, we studied the effects of zeta potential on flocculation and drainage.

BACKGROUND

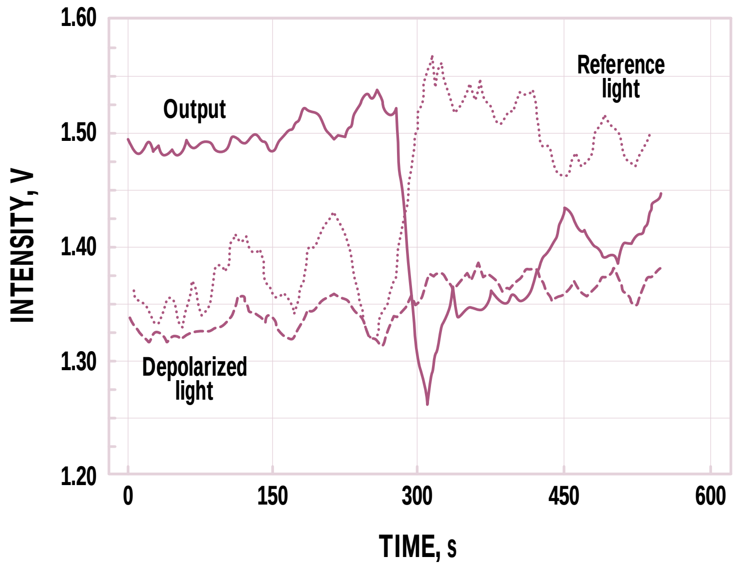
Gess carried out a study to determine how dual retention aid systems affect the drainage of papermaking fibers *(3)*. He found that an anionic polyacrylamide slows the drainage of the fiber mat. Conversely, the rate of dewatering increases with the addition of cationic polyacrylamide. However, Gess used bleached hardwood kraft fibers and did not study the effects of fines and anion trash associated with mechanical pulp.

In another study, Krogerus used a mechanical pulp with 20% filler grade clay *(4)*. He found that drainage was unaffected by the use of medium- and high-molecular-weight cationic polyacrylamide. However, drainage slowed with low-molecular-weight cationic polyacrylamide and slowed even more with anionic polyacrylamide. His results with cationic polyacrylamide are different from the results reported by Gess.

Moberg states that dewatering and retention can both be achieved with microparticle retention aid systems and that various new systems are under development *(5)*. However, most of the successful cases have been reported in the alkaline papermaking of groundwood-free grades. One example is that of Bernier's work with a microparticle retention aid system consisting of cationic polymer and bentonite, which was carried out at an alkaline fine paper mill *(6)*.

Currently, studies are being performed for applying microparticle retention aids to alkaline groundwood furnishes. For instance, using a groundwood furnish, Fitzgibbons *(7)* and Glittenberg *(8)* studied the effectiveness of cationic starch as an anion trash catcher. Scott *(9)* selected cationic starches with different molecular weights and charge densities for different purposes, such as charge neutralization and strength improvement. However, Scott's study did not include the effects of starch on drainage and flocculation. Previous work has shown that a certain type of starch decreases flocculation *(10)*.

In studying a retention aid system consisting of a cationic polyacrylamide and anionic bentonite, Wagberg *et al.* used special equipment to determine the flocculation of bleached softwood kraft pulp *(11)*. They selected a precoverage ratio of the fibers with a polymer of low molecular weight as the important condition for effective flocculation by microparticle systems. However, they did not measure the zeta potential during their study. Penniman measured zeta potential and drainage automatically for the



1. The intensity of the reference light increases with the addition of retention aid. In turn, the increase in the reference light intensity causes a decrease in the output intensity, measured in volts. (100% LBKP, 20% $CaCO_3$ added, 300 ppm cationic PAM).

	Molecular weight, 10^6	Charge density, meq/g
C-PAM systems		
Single polymer	3	1.3
Microparticle	3–5	3.1
A-PAM systems		
Single polymer	10	1.0
Poly-DADMAC	...	7.1

C-PAM = cationic polyacrylamide.
A-PAM = anionic polyacrylamide.
DADMAC = diallyl dimethyl ammonium chloride.

I. Molecular weights and charge densities

microparticle process, but he used chemical pulp and did not perform experiments with a grade of furnish containing groundwood *(12)*.

Moberg said that the wet-end chemistry of an optimized paper machine is not operating at equilibrium *(5)*. The polymer will be most effective after it has had time to reach particle surfaces and bridge them but before it has time to reconfigure itself totally onto the surface. He said that it is the nonequilibrium state that makes it difficult, if not impossible, to simulate the system in the laboratory.

The order of chemical addition is important, but changes in the flocculation and drainage with each chemical addition at the nonequilibrium state have not been elucidated. To evaluate microparticle retention aid systems for alkaline groundwood furnish, we have to measure simultaneously the zeta potential, flocculation, and drainage.

MEASURING PROCEDURES

Zeta potential

Zeta potential was measured based on the streaming potential principle. The measurement was calibrated according to the method reported in a previous study *(13)*.

Flocculation

When a plane-polarized light enters a crystalline material like quartz, the plane of polarization changes to another plane. This phenomenon is called "optical activity." Many substances exhibit optical activity, including solutions of cellulose fiber.

Our instrument is based on this principle. A consistency transmitter used in the paper machine wet end measures both the reference light and the depolarized light, both of which are transmitted through the pulp suspension *(14)*. The reference light is the transmitted light that has the same plane as the incident light. The output from the transmitter is a ratio of the two signals.

$$\text{Output} = 10 \times (DL/RL) \qquad (1)$$

where

DL = intensity of depolarized light
RL = intensity of reference light.

In previous work, this instrument proved useful in monitoring flocculation *(10)*.

Before the retention aid was added, the solution was loaded with filler. The suspended solids scattered the reference light and decreased its intensity. Flocculation caused some of the suspended filler solids to be retained on the fibers, which reduced the amount of suspended fillers. The mass distribution of the pulp and filler suspension also became nonuniform, and incident light could easily pass through the thin local areas between flocs.

Hence, the intensity of the reference light increased with flocculation. The intensity of the reference light is the denominator in Eq. 1. In the calculation, the increase in the reference light results in a decrease in the output value. This occurrence is illustrated in **Fig. 1**, where the output corresponds with the inverse of flocculation. A decrease in the intensity of the output signal reported in volts represents an increase in flocculation.

Drainage

In 1990, Unbehend critically reviewed the laboratory drainage testers *(15)*. He stated that the ideal test would be one that could accurately model the drainage that actually occurs on the paper machine. In addition, it would reflect the effects of the flow velocities, basic fiber properties, consistencies, turbulence, and basis weights encountered during the drainage process. According to Unbehend's report, researchers had tried to incorporate each of these characteristics in various tests, but the perfect drainage tester had not yet been developed.

We have developed an on-line wet-end analysis system, and we have taken it to mills for process optimization and troubleshooting *(16)*. A few years ago, we monitored the performance of a machine producing paper of fine grade. The machine was equipped with an on-line freeness tester on the fiber line. Data from the freeness instrument and measurements of the steam pressure of the paper machine dryers were collected in a computer database and were compared. The two were found to correlate closely. As the freeness increased, the dryer steam pressure decreased. In other words, as the pulp lost water more efficiently, the wet web was holding less moisture as it entered the dryer, where less moisture gave rise to less steam.

The speed of a paper machine that is dryer limited can be increased by an improvement in drainage. One of the primary purposes for using drainage testers is to predict what the drainage will be on the paper machine. Thus, this use of the freeness tester could be applied in our wet end study.

Case	Chemical sequence	Floccula-tion, %	Drain-age, %
Wood-free furnish[a]			
1	A-PAM	0	–14
2	DADMAC, A-PAM	+5	–15
3	Bentonite, A-PAM	+1	0
4	DADMAC, bentonite, A-PAM	+8	–15
5	C-PAM	+5	+ 7
6	DADMAC, C-PAM	+6	+ 4
7	C-PAM, bentonite	+7	+1
8	DADMAC, C-PAM, bentonite	+8	+19
Wood-containing furnish[b]			
9	A-PAM	+1	–7
10	Alum, A-PAM	+5	+38
11	DADMAC, A-PAM	+3	+22
12	Bentonite, A-PAM	+3	+19
13	Alum, bentonite, A-PAM	+4	+37
14	DADMAC, bentonite, A-PAM	+4	+28
15	DADMAC, A-PAM, bentonite	+6	+65
16	C-PAM	+1	+23
17	Alum, C-PAM	+4	+43
18	DADMAC, C-PAM	+3	+42
19	C-PAM, bentonite	+4	+29
20	Alum, C-PAM, bentonite	+7	+50

[a] 100% LBKP. PCC added at 20%. pH = 7.8.
[b] 60% LBKP, 40% groundwood pulp. Talc added at 15%.

II. Summary of flocculation and drainage for wood-free and wood-containing furnishes

The operating principle of the freeness tester is simple. Furnish is drawn through a screen by a vacuum, and a pad forms under the screen. While white water passes through the pulp pad, the level of white water in the chamber is recorded, and the flow rate is calculated as being the pulp freeness.

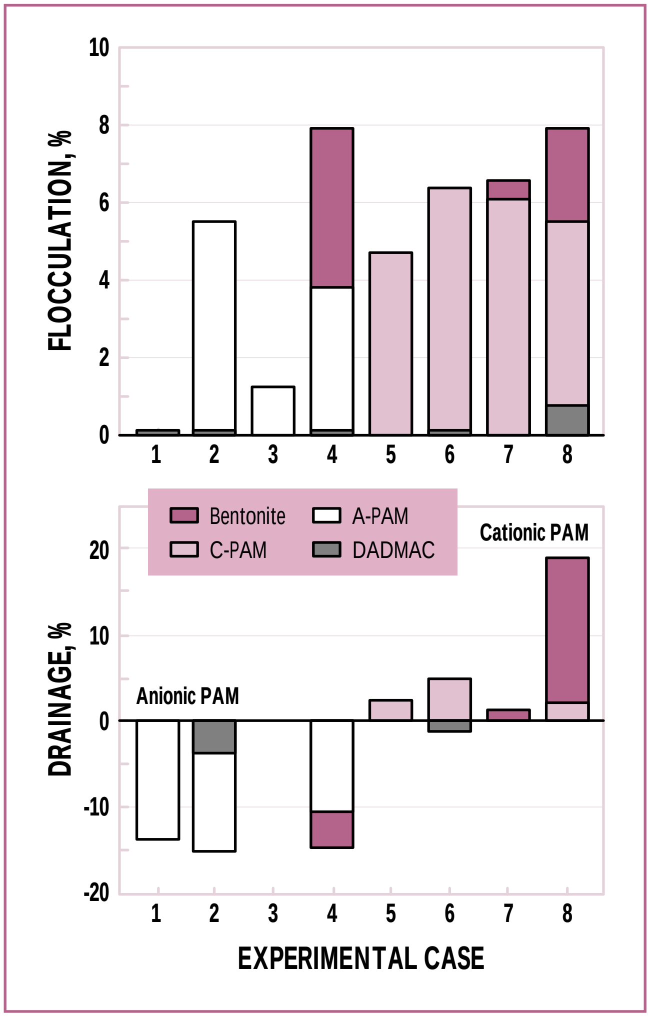
Hence in our laboratory, a CCD (charge-coupled device) camera was installed outside the zeta-potential instrument chamber. By using an image analysis technique, we measure the maximum liquid level, which is converted to the liquid volume. The instrument incorporates the effects of pressure drops, and there is a contribution from the compressibility of the fibrous mass.

From the data of height vs. time, Springer *et al.* calculated the specific filtration resistance and used it as a drainage parameter *(17)*. Instead, we selected the maximum liquid volume as a drainage parameter, based on our analysis of the paper machine. The validity of this method was further confirmed with a laboratory experiment. Bleached hardwood kraft pulp was beaten with a PFI mill to various freeness levels. The drainage of each pulp sample was measured with our instrument and the Canadian Standard Freeness tester. A good correlation was observed between them *(18)*.

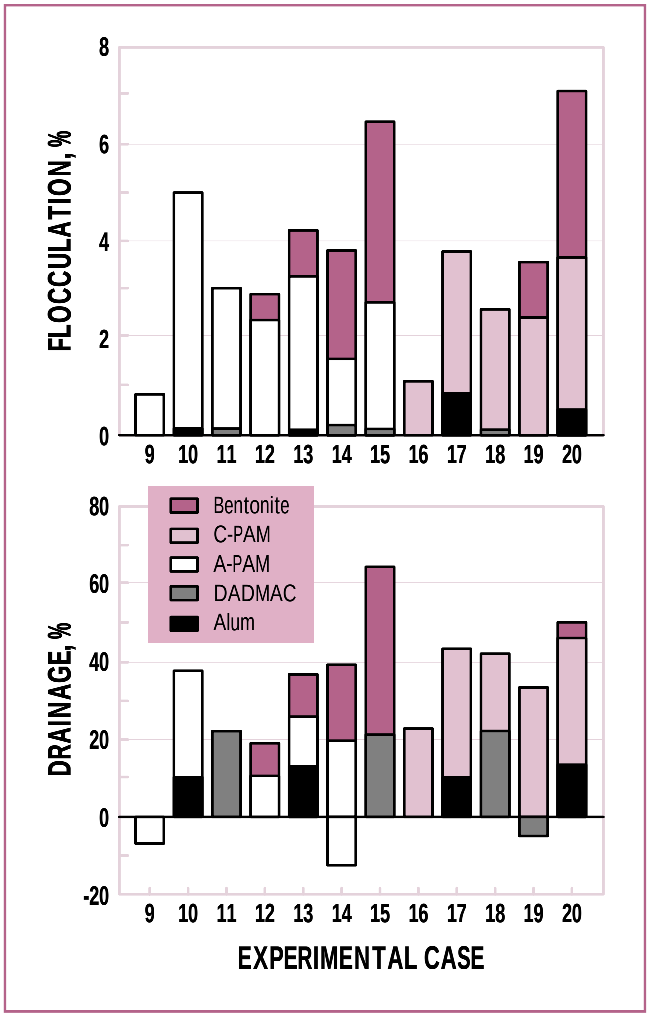
EXPERIMENTAL CONDITIONS

Pulp preparation

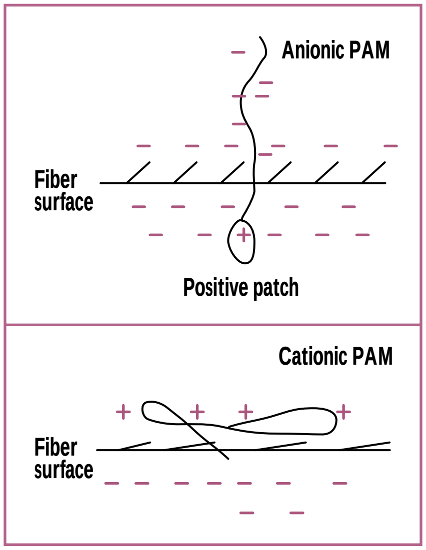
Market bleached hardwood kraft pulp (LBKP) was beaten to a freeness of 450 mL CSF by a pilot single refiner at 3% pulp consistency. Bleached groundwood pulp made from red pine in a mill was also selected for the study. The freeness of the groundwood pulp was 50 mL.



2. Percentages for the groundwood-free grade (100% LBKP, 20% PCC, pH 7.8)



3. Percentages for the furnish grade containing groundwood (60% LBKP and 40% groundwood, 15% talc)



5. Changes of fibrils on the fiber surface, illustrating (top) anionic and (bottom) cationic polyacrylamide adsorption

The pulp consistency of all samples was adjusted to 0.5% with tap water.

For experiments on groundwood-free grades, LBKP was mixed with 20% PCC. The prepared sample had a pH of 7.8, a zeta potential of –15.2 mV, and a drainage of 37.4 mL.

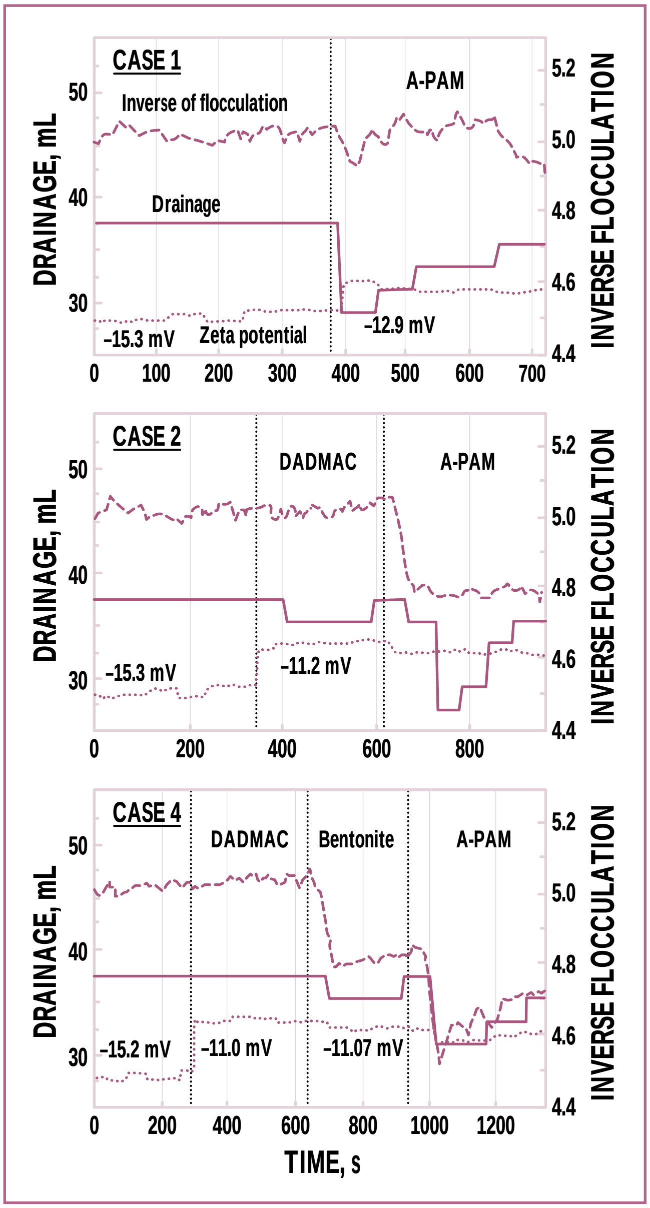
For experiments on groundwood-containing grades, a furnish was prepared from 60% LBKP and 40% groundwood pulp with talc added at 15%. The furnish had a pH of 6.8, a zeta potential of –11.3 mV, and a drainage of 29.0 mL. The low drainage rate was caused by the mechanical pulp fines.

Chemicals

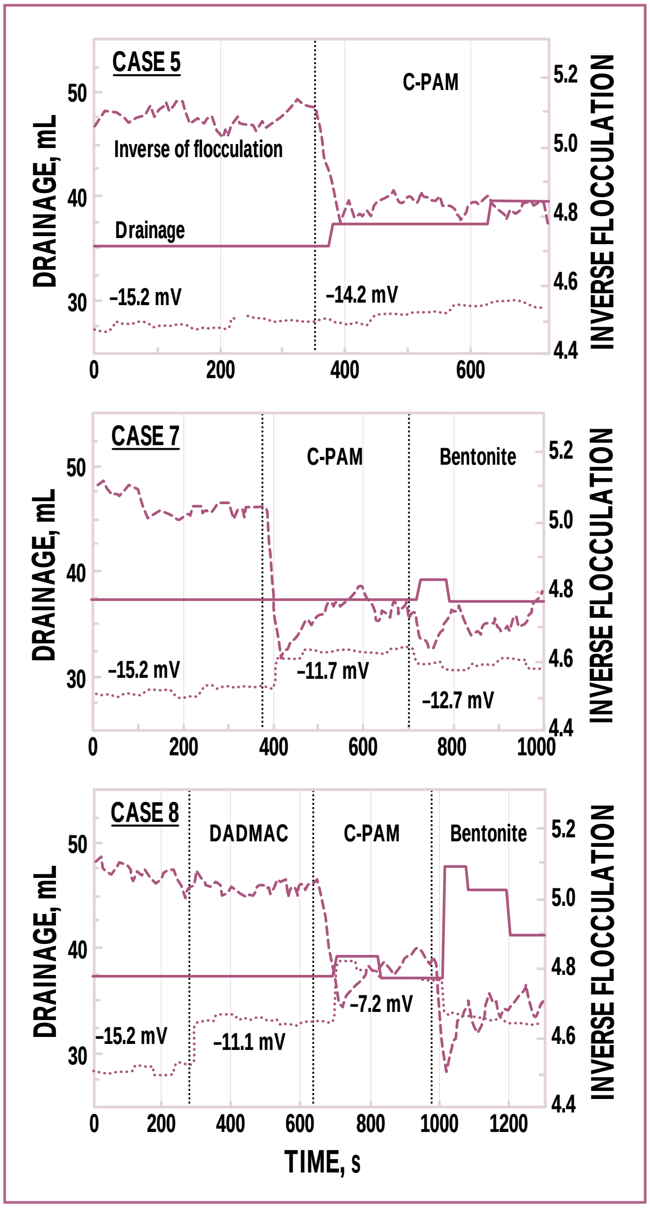
For the best experimental results, conditions at the wet end should not be in a state of equilibrium *(5)*. Therefore, the prepared sample was recirculated by pumps from a small tank to the three on-line sensors and was subjected to the hydrodynamic shear force. Chemicals were added sequentially to the tank. The molecular weights and charge densities of the chemicals used are listed in **Table I**.

Changes of flocculation and drainage

It took 60 s to complete one cycle of drainage and zeta potential measurement. The data logger held old values for 60 s until a new value was measured. Thus, the measurement of drainage (in milliliters) and zeta potential (in millivolts) was discrete, but the output was analog. Similarly, the flocculation measurement was



4. In the groundwood-free grade, anionic PAM was added for Cases 1, 2, and 4. In Case 2, DADMAC was added first. For Case 4, DADMAC was added first, followed by bentonite and then anionic PAM. (100% LBKP, 20% PCC added, pH 7.8)



6. In the groundwood-free grade, cationic PAM was added for Cases 5, 7, and 8. In Case 7, bentonite was added after cationic PAM. In Case 8, DADMAC was added first, followed by cationic PAM and then bentonite. (100% LBKP, 20% PCC added, pH 7.8)

continuous, and the output (in volts) was analog.

Data from the three sensors were stored every 5 s in a personal computer database and were plotted as the line graphs presented here. Percent changes of flocculation and drainage by each chemical addition are summarized in **Table II**. These percentages are broken down in the bar graphs of **Figs. 2 and 3**. Specific numerical values have been published elsewhere *(18)*.

The percent changes were calculated as follows:

$$\text{Flocculation, \%} = [(F_1 - F_2)/F_1] \times 100 \qquad (2)$$

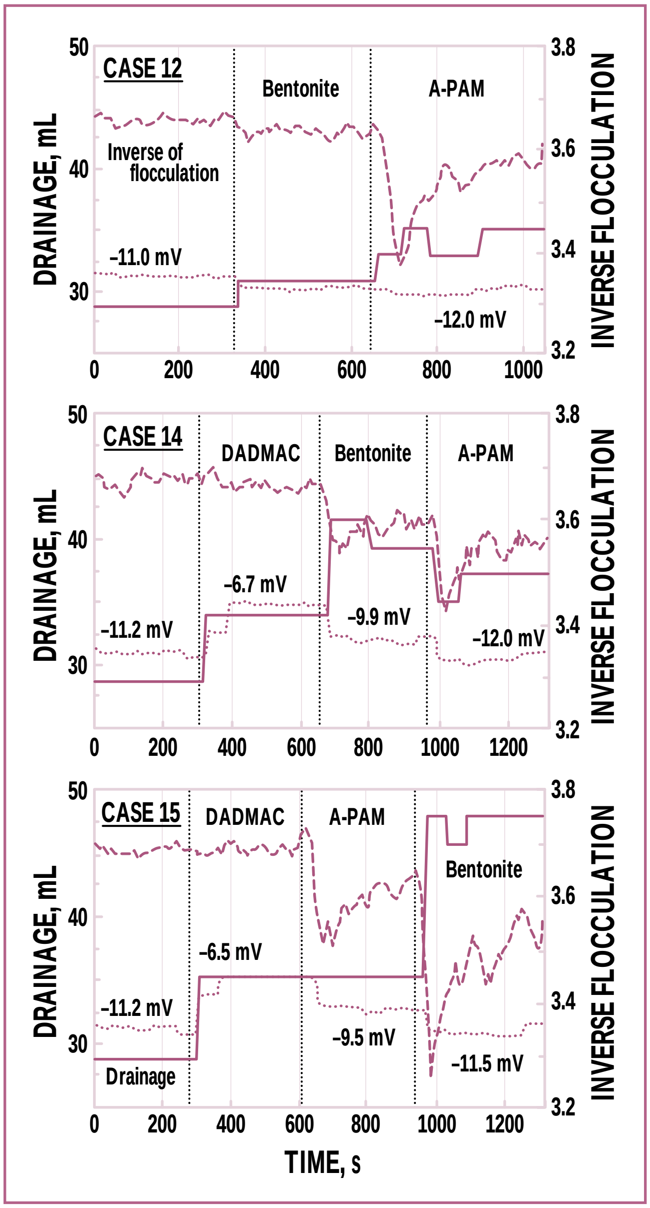
where

F_1 = 5-min average of the output of Eq. 1 before chemical addition, volts

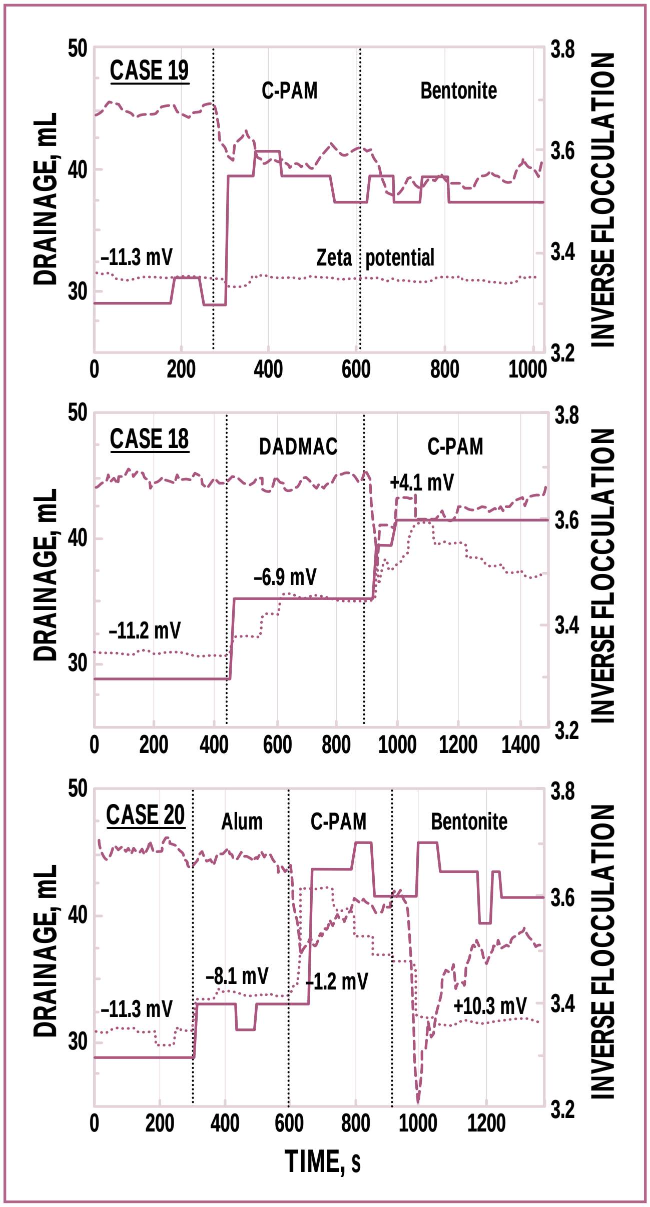
F_2 = 5 min average of the output of Eq. 1 after chemical addition, volts.

$$\text{Drainage, \%} = [(D_2 - D_1)/D_1] \times 100 \qquad (3)$$

where



7. In the groundwood-containing grade, bentonite plus A-PAM made up Case 12. The sequence for Case 14 was DADMAC, bentonite, and A-PAM. For Case 15, the sequence was DADMAC, A-PAM, and bentonite. (60% LBKP and 40% groundwood, 15% talc, pH 6.8)



8. In the groundwood-containing furnish, C-PAM and then bentonite were added in Case 19 (pH 6.8). DADMAC and C-PAM were added sequentially for Case 18 (pH 6.8). For Case 20, the sequence was alum, C-PAM, and bentonite, and the pH was 5.6. (60% LBKP and 40% groundwood, 15% talc)

D_1 = 5-min average of the liquid volume before chemical addition, mL

D_2 = 5-min average of the liquid volume after chemical addition, mL.

RESULTS AND DISCUSSION

The order of chemical addition was critical. We continuously evaluated the effects of chemical additions with monitoring instruments. The furnish was subjected to hydrodynamic shear flows. Changes in the flocculation and drainage were recorded for each chemical addition.

An on-line laboratory system was developed to measure the zeta-potential, flocculation, and drainage of pulp and filler suspensions in the nonequilibrium state. We plotted the raw data from the three sensors on the same graph, as the graphs in the figures reflect. The left axis indicates drainage, and the right axis pertains to flocculation. Zeta-potential data are printed on the graphs as well.

Groundwood-free furnish

Anionic polyacrylamide. The addition of only anionic polyacrylamide (A-PAM) did not make flocs and did decrease drainage (**Fig. 4**, Case 1). The results are in agreement with the results of Gess *(3)* and Krogerus *(4)*, which substantiates the validity of the instruments and experimental methods of this study.

A small increase in zeta potential was observed when anionic polyacrylamide was added. Presumably, anionic polyacrylamide precipitates a certain amount of cationic material that is suspended or dissolved in the sample. As it precipitates, the cationic material is deposited on the fiber surface, increasing the surface charge of the fibers. The zeta potential instrument measures the surface charge of the whole pulp, including fibers, and the zeta potential value increases.

When we added poly-DADMAC before adding anionic PAM, the zeta potential increased from –15 mV to –11 mV. When the anionic polyacrylamide was added, flocculation resulted, but the drainage was still slow (Case 2). Bentonite and anionic polyacrylamide induced little flocculation, and no improvement in drainage was gained (Case 3, Table II). A microparticle retention aid system composed of poly-DADMAC, bentonite, and anionic polyacrylamide gave the most extensive flocculation, but it also reduced the drainage (Case 4).

In short, flocs formed with anionic polyacrylamide when the zeta potential had been properly controlled in the range of about –11 mV to 0 mV, but the drainage decreased. Cationic coagulants such as alum and poly-DADMAC first react with the soluble anionics. The cationic coagulants then react with fines and fillers because they have a large specific surface area. When more chemical is added, it adsorbs on the long fiber surface. In previous work, the coagulant's reaction with the solubles and fines of a newsprint furnish was completed at a zeta potential of –10 mV *(13)*. In the work presented here, the corresponding zeta potential was about –11 mV, which is close to –10 mV.

In Case 1, the zeta potential was highly negative, and anionic polyacrylamide did not adsorb on fibers and fines. Anionic polyacrylamide seemed to work as a dispersant and did not make flocs. But even when the charge was neutralized in Case 2, anionic polyacrylamide adversely affected drainage.

The mechanism of the reaction of anionic polyacrylamide may be that the highly charged poly-DADMAC creates a positive patch on the fibers and fines. Anionic polyacrylamide is then adsorbed on that positive patch, as the upper illustration in **Fig. 5** depicts. The anionic polyacrylamide molecular chains, which bond to a cationic patch on another surface, create flocculation by the bridging mechanism. However, fibrils of the fiber surface are known to decrease drainage. Anionic polyacrylamide, which bonds indirectly on the fiber surface, does not affect the fibrils and does not improve drainage. On the other hand, the loops and tails of free anionic polyacrylamide, which do not bond, prevent the smooth flow of water in a pulp mat and decrease drainage.

Cationic polyacrylamide. As a single retention aid, cationic polyacrylamide created flocculation, but we observed little improvement in drainage (**Fig. 6**, Case 5). A greater increase in flocculation occurred when the cationic polyacrylamide was preceded by poly-DADMAC (Case 6, Table II). The sequential addition of cationic polyacrylamide and bentonite increased flocculation, yet the drainage improvement was inadequate (Fig.6, Case 7).

The greatest improvement in drainage among all of the groundwood-free grade experiments was achieved with a microparticle system with the addition of poly-DADMAC, cationic polyacrylamide, and then bentonite (Fig. 6, Case 8). Most of the drainage improvement was achieved by bentonite, and the extent of the improvement was strongly influenced by charge neutralization. Charge neutralization with poly-DADMAC by itself did not affect flocculation or drainage, but it enhanced the effectiveness of cationic polyacrylamide and bentonite.

Cationic polyacrylamide is absorbed directly on the fiber surface, and increased retention occurs by the bridging mechanism. Cationic polyacrylamide improved drainage just a little. Presumably, the cationic polyacrylamide collapsed a small amount of fibrils onto the fiber surface, resulting in a decrease in hydrodynamic specific surface area (Fig. 5, lower illustration). Macroflocs, which are created by cationic polyacrylamide, are broken down by hydrodynamic shear force into small particles. Bentonite reflocculates them into microflocs and improves drainage.

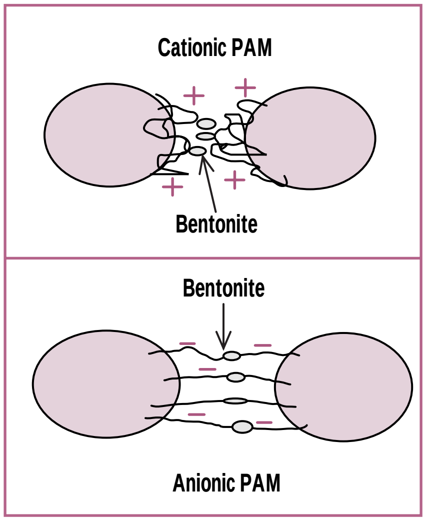
Groundwood-containing furnish

Overall changes in flocculation and drainage did not seem to oppose each other. But when we examined them carefully, we found that several chemical additions created different responses in flocculation and drainage.

Anionic polyacrylamide. Used alone, anionic polyacrylamide produced little flocculation and decreased the drainage (Case 9, Table II). When bentonite was added first, flocculation and drainage increased when anionic polyacrylamide was added (**Fig. 7**, Case 12). However, flocculation and drainage did not reach the same levels obtained with alum in the acid papermaking system (Case 10, Table II).

Charge neutralization with poly-DADMAC increased the drainage by itself (**Fig. 7**, Case 14), in contrast to the results with the groundwood-free furnish. We assume that the pulp containing groundwood has many fines, which plug the pores of the fiber network and prevent water flow through the pulp mat. With charge neutralization, fines are adsorbed on the fiber surface, opening the pores of the fiber network and increasing the permeability.

According with the results for the groundwood-free furnish, however, flocculation did not occur by charge



9. Proposed drainage models, illustrating (top) the bridge model and (bottom) the patch–bridge model

neutralization alone. A microparticle system of poly-DADMAC, bentonite, and anionic polyacrylamide increased both flocculation and drainage (Fig. 7, Case 14). In looking closely at flocculation and drainage with each chemical addition, we see that a final addition of anionic polyacrylamide decreased drainage. Anionic polyacrylamide works as a single polymer, without creating a microparticle structure.

When we reversed the order of bentonite and anionic polyacrylamide, flocculation and drainage increased further (Fig. 7, Case 15). This microparticle system of poly-DADMAC, anionic polyacrylamide, and then bentonite was the best system for the groundwood furnish. As we analyzed and compared the graphs for Cases 14 and 15, we found that the system can register changes in flocculation and drainage with each chemical addition, which is the great advantage of this system.

Cationic polyacrylamide. Cation-ic polyacrylamide improved drainage but produced little flocculation (Case 16, Table II). Bentonite affected neither drainage nor flocculation (**Fig. 8**, Case 19). In alkaline papermaking, poly-DADMAC effectively neutralized the charge, and it increased the flocculation and drainage of cationic polyacrylamide (Fig. 8, Case 18).

In acid papermaking, alum worked as a charge neutralizer, and it also affected greatly the flocculation and drainage when followed by cationic polyacrylamide (Cases 17 and 20, Table II). Further addition of bentonite after cationic polyacrylamide in acid papermaking increased flocculation but did not contribute to drainage improvements (Fig. 8, Case 20).

Microparticle systems composed of cationic polyacrylamide and bentonite were not suitable for the groundwood furnish. No drainage improvement was observed when bentonite was added, even if a charge neutralizer was added beforehand. By contrast with the optimum conditions for the groundwood-free grade, the most suitable microparticle system for the furnish containing groundwood consisted of poly-DADMAC, anionic polyacrylamide, and bentonite (Case 15). (For the groundwood-free furnish, the best sequence was poly-DADMAC, cationic polyacrylamide, and bentonite.)

In the system of poly-DADMAC and cationic polyacrylamide, cationic polyacrylamide forms a bridge between particles, as **Fig. 9** illustrates. The surface charge of the particles is negative. The loops of the adsorbed cationic polyacrylamide molecules tend to be attracted to the particle surface, and the cationic molecule reconfigures itself on the particle. The distance between bridged particles is short.

The case of poly-DADMAC and anionic polyacrylamide is quite different. Anionic polyacrylamide anchors on the positive patch on the particle surface created by poly-DADMAC. The loops of anionic polyacrylamide molecules are repelled by the negatively charged particle surface and are long enough to be extended from the particle surface. The distance between particles in the patch–bridge model of anionic polyacrylamide is longer than in the bridge model of cationic polyacrylamide. Bentonite, because of its amphoteric nature, forms a co-bridge between polymers of both positive and negative charges. Mechanical pulp fines in groundwood-containing furnish are adsorbed on the particle surface by charge neutralization.

In the bridge model of cationic polyacrylamide, the short distance between particles and adsorbed fines slows the water flow between particles. In the patch–bridge model of anionic polyacrylamide, the particles are more distant. The distance allows the water to flow smoothly between particles, even if the fines are adsorbed on the particle surface.

CONCLUSIONS

Our study is aimed at one of the needs in alkaline papermaking, the need to improve flocculation and drainage. The instrument system we have developed can measure drainage, flocculation, and zeta potential simultaneously. In making comparisons to find optimum conditions, we have used various additives including alum, anionic polyacrylamide, cationic polyacrylamide, bentonite, and poly(diallyl dimethyl ammonium chloride). Here, we have reported results from experiments on both a groundwood-free furnish and a furnish containing groundwood.

For the groundwood-free furnish, charge neutralization did not affect flocculation, nor did it affect drainage by itself. However, charge neutralization enhanced the effectiveness of polymers (Cases 2, 4, 6, and 8).

Anionic polyacrylamide made flocs when the zeta potential had been properly controlled, but anionic polyacrylamide decreased drainage (Case 2). Cationic polyacrylamide improved flocculation greatly, but the drainage increase was very small (Cases 5 and 6). Flocculation and drainage did not always show the same response to chemical additions (Cases 1–4). Therefore, it is important to measure flocculation

KEYWORDS

Acrylamide, acrylic compounds, addition polymers, alkaline papers, amides, drainage, electrical properties, flocculation, free sheet, ground wood, mechanical pulps, paper grades, papermaking, polyacrylics, retention aids, specialty papers, zeta potential.

and drainage concurrently in evaluating retention aid systems.

A microparticle system of poly-DADMAC, bentonite, and anionic polyacrylamide resulted in strong flocculation but decreased drainage (Case 4). A microparticle system of poly-DADMAC, cationic polyacrylamide, and bentonite greatly improved both flocculation and drainage, with a considerable improvement in drainage with the addition of bentonite (Case 8).

For the furnish containing wood, by contrast, charge neutralization increased drainage by itself. Alum was effective in acid papermaking (Cases 10, 13, 17, and 20), and poly-DADMAC was effective in alkaline papermaking (Cases 11, 14, 15, and 18). Flocculation did not occur by charge neutralization alone.

Sequential addition of poly-DADMAC, bentonite, and anionic polyacrylamide improved the total flocculation and drainage (Case 14). However, the drainage improvement by anionic polyacrylamide was negative. When we reversed the order of bentonite and anionic polyacrylamide, the sequential addition of poly-DADMAC, anionic polyacrylamide, and bentonite further increased flocculation and drainage for a microparticle system and was also the best for the groundwood-containing grade (Case 15).

The increase in drainage with this system was more than 60% (Case 15) for the furnish containing groundwood, while it was less than 20% with the best retention aid system for the groundwood-free furnish (Case 8). The microparticle system was more effective for the groundwood furnish than for the groundwood-free furnish. The explanation of these differences could be that the furnish with groundwood has a large amount of mechanical pulp fines that plug the pores of the fiber network and decrease drainage. Charge neutralization or flocculation can make fines adsorb on the fiber surface, opening the pores of the fiber network.

Most of the drainage increase of the microparticle system was achieved by bentonite addition, and it was strongly influenced by charge neutralization (Case 8 and 15). Thus, the zeta potential should be properly controlled in microparticle systems. **TJ**

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