Reversibility of Polymer-Induced Fiber Flocculation by Shear. 2. Multi-Component Chemical Treatments

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SUMMARY:

Optical and viscometric tests showed essentially complete dispersal of fiber flocs when polymer-treated chemithermomechanical (CTMP) fiber slurries were exposed to intense shear in a blender. Two types of chemical systems showed evidence that flocs formed again after the shear application were stronger or larger than those in an untreated slurry. An optical test showed that treatments that included poly-diallyldimethylammonium chloride (DADMAC) yielded a charge-dependent maximum in fiber flocculation that approximately corresponded to charge neutralization. By contrast, only a viscometric test showed a net increase in fiber flocs after treatments with cationic polyacrylamide (cPAM) following by nano-size anionic materials (microparticles) and intense shear. In certain cases the polyelectrolyte-induced bonds holding calcium carbonate filler particles to the fibers or to each other within the slurry appeared sufficient to withstand intense shear almost completely. Results support strategies in which hydrodynamic shear in a papermaking system helps to minimize fiber flocs, while leaving polymeric attachments to filler particles intact.

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According to Hedborg and Lindström (1996), slurries of papermaking fibers flocculated by a single, high-mass cationic polyelectrolyte may be redispersed irreversibly when exposed to sufficient levels of hydrodynamic shear. Tests with a Britt Dynamic Drainage/Retention Jar (BDDJ, Britt 1973) show a reduced tendency of the flocs to re-form after the level of agitation is reduced. By contrast, certain sequential combinations of chemical flocculants yield reversible flocculation. Those fiber flocs are able to form again to approximately the same degree after they have been broken down by strong agitation. Examples of highly reversible systems include sequential treatment by cationic starch and colloidal silica.

Among the most persuasive demonstrations of strong, but reversible flocculation is provided by Swerin *et al.* (1997a), who report work with suspensions of microcrystalline cellulose. Repeated cycles of floc breakdown and recovery are shown when suspensions treated with cationic polyacrylamide (cPAM) or cPAM followed by

colloidal silica are exposed to alternating high and low agitation levels in a BDDJ apparatus.

Concern about the shear levels applied in a BDDJ-type test arises in light of work reported by Li and Scott (2000). Micrographs compare the sizes of agglomerates of clay filler, formed as a result of treatment by flocculant. The results imply that the shear levels applied during a BDDJ test may be insufficient to disperse all of the flocs in a papermaking furnish and that the degree of flocculation of fine particles may differ from that of the fibers in the same slurry. A study by Tam Doo *et al.* (1984) shows that the maximum shear present during BDDJ tests is substantially lower than that present in certain unit operations the Fourdrinier system considered.

As shown in a report by Ericksson and Alm (1993), it is possible to address issues of floc reversibility and higher shear by use of an optical floc-sensing device, the PDA 2000 (see also Krogerus 1993). In their study, polystyrene latex flocculated by high-mass cationic polymers is found to reflocculate with a high degree of reversibility after application of controlled shear in a separate part of the device. The present work includes a modification of the PDA 2000 so that experiments can be conducted in the presence of fibers (Hubbe 2000). Related methods of evaluating fiber flocculation by optical (Swerin *et al.* 1993; Alfano *et al.* 1999) or rheometric methods (Swerin 1998) are reported.

The present experimental work deals with effects of a high-charge cationic polymer, followed by other chemical treatments. Previous work suggests that flocculation by high-mass acrylamide copolymers may be more effective if the pulp slurry is pretreated by such materials (Swerin *et al.* 1997b). Suggested reasons for such benefits include neutralization of excess anionic colloidal charge (Dixit *et al.* 1991; Lorz, Linhart 1993; Kuhn 1998), and the need for anchoring sites in the case of an anionic acrylamide copolymer (Wågberg, Lindström 1987; Davidson 1989; Jaycock, Swales 1994). Swerin *et al.* (1997b) propose an alternative mechanism called “site blocking” to account for the same kind of enhancement, even in well-washed fiber systems. According to the site-blocking mechanism, the high-charge cationic polymer molecules partly cover the fiber surfaces so that the large cPAM molecules are not able to lie down flat on the fiber surfaces. The extended loops and tails of the flocculant ought to be more effective for creating of bridges between fiber surfaces and with fine particles.

So-called microparticle systems also were evaluated in the present work. The two best-known systems of this type each involve addition of a high-mass cationic polyelectrolyte to the furnish, followed by a colloidal mineral such as colloidal silica (Andersson *et al.* 1986) or montmorillonite (Langley, Litchfield 1986; Swerin, Ödberg 1996; Wågberg *et al.* 1996). More recently, Honig *et al.* (1993,2000) show that a highly branched, highly anionic micropolymer can be used with similar effect. In these systems most commonly the high-mass cationic polyelectrolyte is added to the paper machine system ahead of a set of pressure screens, causing the initial fiber flocs to be redispersed. Subsequent addition of the anionic colloidal component downstream of the screens is known to promote rapid drainage. Advances in understanding of these systems are reported (Andersson, Lindgren 1996; Swerin *et al.* 1996; Swerin, Ödberg 1996).

The purpose of the present work is to evaluate the reversibility of chemically induced fiber flocs after they have been exposed to a higher level of hydrodynamic shear than in most previous studies (*e.g.* Forsberg, Ström 1994; Swerin *et al.* 1997a), ensuring their complete disruption. The goal is to show results of parallel tests, including

viscometric and optical measurements of fiber flocculation, drainage rate testing, turbidity as a measure of fine-particle retention, and microelectrophoresis. A further goal is to evaluate the effects of pretreatment of fiber slurry with a highly charged cationic polymer, before addition of (a) a high-mass cationic flocculant, (b) a high-mass anionic flocculant, or (c) a combination of high-mass cationic flocculant, followed by anionic microparticles.

Chemithermomechanical (CTMP) pulp represents an interesting case to study, due to its relatively high anionic charge (Lloyd, Horne 1993; Mikkonen, Eklund 1998). High anionic colloidal charge can be expected due to residual fatty and resin acids, hemicellulose, and sulfonated lignin byproducts in the CTMP. In addition, ground calcium carbonate filler is known to contain anionic dispersing materials such as phosphates.

Materials

Pulp Furnish

Bleached softwood chemithermomechanical pulp (BCTMP) was obtained from Quesnel River Pulp Co. The mixture employed during the work described consisted of 80% product Q120/60 and 20% Q400/B70. In each case the number preceding the slash indicates the nominal Canadian Standard Freeness in ml. The cationic demand of the furnish was 50 meq/L, based on the amount of poly(DADMAC) required to achieve an electrophoretic mobility value of zero after a blending treatment that followed chemical addition (Hubbe 2000). The ground calcium carbonate used was Omyafil® from Omya, Inc., having a reported mean particle size (by sedimentation velocity) of 0.7 μm and a surface area of 11.6 m^2/g . A master batch was prepared in which the fiber solids were 0.5% and the mineral solids were 0.05%.

Chemicals

Polymeric additives were prepared with distilled water by diluting the following commercial products.

The cationic polyacrylamide (cPAM) was an emulsion product EKA PL® 2410 from Eka Chemicals. This cPAM product has a 10% molar charge content and a molecular mass of 9 to 12 million Daltons. A sample of anionic polyacrylamide (aPAM) was Bufloc® 606 from Buckman Laboratories, Inc. The aPAM product is described as having a molecular mass of 30-32 million Daltons and a charge density of 30-32% of the repeating units at full ionization. Both PAM products were diluted to 0.5% of the as-received concentration, and both were evaluated on an “as-received” basis.

Effects of two highly charged linear poly-diallyldimethylammonium chloride (DADMAC) products were compared. The “low mass” polyDADMAC was Alcofix® 169 from Ciba Specialty Chemicals, a product with a nominal molecular weight of 300,000 Daltons. The “high mass” polyDADMAC was Alcofix® 109, having a nominal weight of 1 million Daltons. Both were diluted to 0.1% active polymer and they were used on an “actives” basis.

The colloidal silica used in this work was Compozil® BMA 780 from EKA Chemicals. This colloidal silica product is known as “structured” silica, comprised of chains of colloidal silica particle subunits. This type of product is well described by

Andersson and Lindgren (1996). The advantage of the structured silica particles is that they provide greater increases in retention of fine particles, compared to conventional colloidal silica particles.

The bentonite was an alkali montmorillonite powder product Hydrocol® 2D7 from Ciba Specialty Chemicals. Knudson (1993) provides an excellent review of this type of product. The microparticle products were diluted with distilled water and used on an “actives” basis.

The organic micropolymer product was Polyflex+® CP.3 from Cytec Industries, as reported by Honig *et al.* (1993,2000). The producer describes this product as a water-soluble, anionic filamentary micro-network.

Methods

Fiber Slurry Stirring, Pumping, and High Shear Application

Aliquots of 400 ml of furnish were stirred at the “2.5” setting of a Fisher brand weight-activated magnetic stirrer (Catalogue 14-505-21). This was just sufficient to prevent settling of the fibers. After addition of each chemical, stirring was continued for 15 seconds to ensure mixing (Hubbe 2000).

An intermediate level of hydrodynamic shear was obtained during the course of an optical test (see later). Fiber slurry was pumped at a rate of 530 ml/min with a Masterflex Easy-load model 77601-10 peristaltic pump with 6.35 mm diameter Tygon® tubing. The pumping was operated for 60 seconds during each test.

A high level of hydrodynamic shear was applied by placing 400 ml of fibrous slurry in a standard Waring Blender and agitated at the “blend” setting for 30 seconds.

Optical and Viscometric Tests of Fiber Flocculation

Tests used to sense the effects of chemicals on fiber flocculation were the same as those described in the companion article (Hubbe 2000). The first of these was an optical test. Briefly, the relative intensity of fiber flocculation was evaluated with a newly modified version of the Photometric Dispersion Analyzer PDA 2000 (Low Gain Version) from Rank Brothers, Ltd. The Low Gain Version has a modified sensing zone, making it possible to observe effects of fiber flocs in a clear tube having an inner diameter of 6.35 mm. Fiber slurry, as described above, was pumped from a gently stirred beaker, through the floc-sensing device, and back to the beaker. Tests were carried out with the electronic filtering option selected and with the “RMS” option to report the root-mean-squared fluctuating component of light transmitted through the tube. The test appears to be especially sensitive to charge-related mechanisms of fiber flocculation.

Additional data related to fiber flocs were obtained with a Brookfield digital viscometer, using a modified probe (Hubbe 2000). This test employed a modified probe, consisting of a pair of 6mm-diameter rods, placed symmetrically parallel to the axis of the viscometer and spaced 50 mm apart. These were dipped 50 mm into stagnant fiber slurry samples for each test. The viscometer was run at a rotational speed of 50 rpm. and data were collected from the “percent” scale. Observations suggest that the results of this test depend on the sizes of fiber flocs that collect onto the lead edge of each probe as the probes move through the fiber slurry. It has not been determined whether flocs of fibers collected in this manner more often tend to break in the middle, or whether they more

often tend to roll or slide off to one side or the other of the probe. The test appears to be sensitive to polymer bridging-type associations among fibers.

Supplementary tests were carried out as described earlier to evaluate effects of the chemical treatments on filler retention, drainage rates, and the moisture of a fiber pad after a standardized vacuum application (Hubbe 2000). Electrophoretic mobility data were obtained with an SKS Charge Analyzer, Model II from SKS Associates of North Hampton, NH.

Results and Discussion

Effects of Dual-Cationic Polymer Treatments

As shown in Part 1 of this series (Hubbe 2000), treatment of CTMP fiber slurries with individual cationic polyelectrolytes yielded substantial flocculation. In the case of treatment with high-mass cPAM the fiber-fiber flocs were broken irreversibly by shear in a blender. In the case of poly(DADMAC) the optical test showed a maximum flocculation and a maximum ability of flocs to form again after shear when the zeta potential was near zero. Table 1 summarizes some results of sequential addition of the two polymers.

The reversible nature of fiber flocculation in the absence of chemical treatment is shown by data in the first numerical column in Table 1. It is notable that the viscometric test yielded values of 19.7, 21.0, and 19.3 initially, after peristaltic pumping, and after high-shear blending, respectively. These values are within one standard deviation of the mean for repeat measurements, based on the statistics shown earlier (Hubbe 2000). Likewise the optical method yielded values of 0.11, 0.12, and 0.12, indicating that there was no measurable difference. Results in Table 1 also show that similar values of drainage times, and fiber-pad moisture after vacuum application were obtained before and after blending, in the absence of polymeric additives.

Treatment with cPAM produced initial increases in flocculation, as shown by both the viscometric and optical tests, regardless of the level of prior treatment with poly(DADMAC). After application of shear with a blender the fluctuations in light intensity decreased to level of the baseline values, indicating full breakdown of the flocs and no significant reflocculation above the level of untreated fibers. These results are consistent with descriptions of “hard flocs” (Unbehend 1976) and a bridging mechanism of flocculation (Gregory 1973).

The fact that Swerin *et al.* (1997a) report reversible flocculation with cationic polyacrylamide, unlike the present results, is tentatively attributed to a lower level of applied shear in that study. Lower shear makes it more likely that loops and tails of polymer remain extended from the surfaces of fibers in the slurry after shear application. Though some unit operations such as pressure screens involve very high levels of hydrodynamic shear (Tam Doo *et al.* 1984), it is worth noting that individual fibers are exposed to maximum shear levels very briefly. Also, the smaller size of microcrystalline cellulose used in the cited work (Swerin *et al.* 1997a), compared to fibers, would be expected to result in less frictional stresses between the surfaces.

It is worth noting, with reference to Table 1, that increased effectiveness of the cPAM flocculant might be expected if it is assumed that the poly(DADMAC) is acting as a site-blocker, preventing the loops and tails of cPAM from lying down flat on the fiber

surfaces (see Swerin *et al.* 1997b). The present results do not provide evidence for such a mechanism.

Figure 1 shows results of the viscometric tests. Results obtained after peristaltic pumping of the flocculated slurry (dashed line) indicate substantial breakdown of flocs. Results obtained after high-shear blending were not significantly different from the untreated blank (indicated by the arrow), except in the case of the highest level of poly(DADMAC) pretreatment.

A reversibility index corresponding to the viscometric results in Fig. 1 can be defined as follows,

$$RI = [V_2 - V_{\text{blank}}] / [V_1 - V_{\text{blank}}] , \quad [1]$$

where V_1 is the viscometer output in the case of a fiber slurry freshly-treated with flocculant, V_2 is the corresponding data after application of intense shear, and V_{blank} is the viscometer output in the absence of flocculant use. This equation, when applied to the information in Fig. 1, yielded values between zero and 24%. These values are low, compared to results obtained by Hedborg and Lindström (1996), based on retention tests. This implies that disruption of flocs formed by the dual-cationic treatments was mostly irreversible at the high levels of shear used in this study. The results are consistent with the breakage of “hard flocs” (Unbehend 1976) that result from polymer bridging (Gregory 1973).

Although results shown in Table 1 showed that the level of pretreatment with poly(DADMAC) had little effect on most of the observed variables, there was a marked effect on the turbidity of the filtrate collected during vacuum dewatering. Treatment with 0.1% cPAM by itself reduced the filtrate turbidity to 147 NTU, compared with 331 NTU in the case of the untreated blank. Pretreatment with 0.05% poly(DADMAC) before the same level of cPAM yielded 46 NTU.

It is worth noting that high-shear blending yielded almost complete redispersal of the fine material in the furnish (dominated by calcium carbonate filler) in the case of treatment by cPAM alone. In contrast, the retention remained very high even after shear in the case of the dual-cationic polymer treatments. These results are in essential agreement with results shown in Fig. 2, based on tests with poly(DADMAC) alone. It is concluded, based on the full set of results for cationic polymers, that the applied shear was sufficient to break polymer-induced fiber-to-fiber contacts, but it was not sufficient to break apart fillers that had become attached to fibers due to the presence of poly(DADMAC). This mechanism is consistent with a hypothesis by McKenzie (1968) that fiber-to-fiber contacts are more easily broken, compared to fiber-to-fine-particle contacts in a slurry. The hypothesis is also consistent with results of a study by Hubbe (1985, 1986), showing that smaller particles are more difficult to detach from a surface exposed to hydrodynamic shear.

Effects of Dual Treatments with Cationic and Anionic Polymers

As shown in Fig. 3, treatment of the anionic furnish with 0.1% of aPAM (as-received basis) had little effect on the degree of flocculation. By contrast, large increases in floc strength were observed in those cases where aPAM addition had been preceded by treatment with poly(DADMAC). It is worth noting that essentially the same results were

achieved if the poly(DADMAC) was added freshly, or whether the system was “aged” for 45 minutes before addition of the anionic flocculant. These results are surprising in light of work by Forsberg and Ström (1994). To explain these results it is proposed that either of the poly(DADMAC) treatment conditions met the requirement of having sufficient anchoring points for the anionic flocculant. It is further assumed that after such treatment the density or quality of anchoring points was not a dominant variable.

Results for the dual cationic/anionic systems shown in Fig. 3 were similar to cPAM treatment with respect to the effect of shear. Even the relatively mild shearing action of peristaltic pumping destroyed most of the floc strength resulting from the combination of cationic high-charge pretreatment and anionic PAM treatment. Reversibility index values, based on results obtained after blending, were only in the range of zero to about 11%.

As shown in Fig. 4 the effect of aPAM treatment on drainage was either positive or negative depending on the charged state of the system. In the absence of the high-charge cationic polymer aPAM increased the drainage time (see filled histogram bars). Miyanishi and Motegi (1996) report a similar observation where aPAM tended to slow drainage. In contrast, the combination of poly(DADMAC) followed by aPAM promoted drainage. It is notable that when the furnish samples in Fig. 4 were exposed to high levels of hydrodynamic shear, all of the results approached those of the untreated blank. This result suggests that the conditions of blending were sufficiently severe to break down the acrylamide polymers and render them ineffective in terms of either drainage promotion or its inhibition, depending on whether cationic anchoring points were present on the fiber surfaces. Other studies document cases where retention aid molecules are broken down when exposed to shear in fiber suspensions (Sikora, Stratton 1981; Tanaka *et al.* 1993).

Retention results for the systems treated with the anionic flocculant are shown in Fig. 5. Again, the anionic polymer by itself was ineffective, consistent with its expected inability to adsorb onto the untreated, anionic furnish solids. The results for the systems pretreated with poly(DADMAC) before aPAM mirror those shown earlier for cationic flocculant by itself (Hubbe 2000).

Effects of Microparticle Retention and Drainage Aid Systems

As shown in Fig. 6, all three microparticle systems evaluated yielded increases in viscometer output relative to what was achieved by a standard treatment with low-mass poly(DADMAC) followed by cPAM alone. The relative sizes of the black histogram bars show that the greatest floc strength was observed immediately following the microparticle treatment in each case. The relative sizes of the gray bars show that substantial floc strength remained after exposure to peristaltic pumping action. Finally, the relative sizes of the unfilled bars show that there was a relatively small residual positive effect of microparticle treatment on floc strength even after intensive shearing. The fact that the residual effect was much lower than might be expected from some previous work (Swerin *et al.* 1997a) suggests that the high shear in the blender was sufficient to change the nature of loops and tails of polyelectrolyte left over after the initial floc breakage. For instance, it is worth considering whether an intense shear field accelerates the rate at which the polyelectrolytes adopt a flat adsorbed conformation.

Optical data related to flocculation followed similar trends for the three microparticle types. Because the shear stress in the blender was more than sufficient to redisperse the fibers, it follows that the observed fiber flocs were able to recover, at least partially.

It is worth noting that the systems compared in Fig. 6 do not necessarily represent optimum treatment conditions for the given additives. For example, it is known that the performance of the micropolymer is enhanced in systems that contain aluminum ions, and none were used in the present work. Differences in the furnish types, addition points, and papermaking equipment between paper machines make it advisable to run trials with various different chemical programs to find which combination best meets the objectives of process efficiency, product attributes, and cost.

Figure 7 shows further results as a function of poly(DADMAC) dosage in systems that also involved subsequent treatment with cPAM followed by colloidal silica. To a certain extent these results mirror those shown earlier for poly(DADMAC) alone (Hubbe 2000). Thus, a maximum in floc strength was achieved at an intermediate level of the highly charged cationic polymer. Peristaltic pumping action reduced the viscometer output, as in the earlier case without subsequent addition of cPAM and colloidal silica. And finally, high shear treatment appeared to shift the optimum dosage of the high-charge cationic polymer to higher dosages. All these observations are consistent with electrostatic double layer forces being of critical importance to the optimization of this type of chemical program. The apparent optimization of the microparticle effects at electrokinetic neutrality is consistent with the work of Wall *et al.* (1992). These observations are consistent with the charge-dependent and more reversible nature of bonds formed as a result of micro-particle programs (Swerin 1998).

As shown in Fig. 8, drainage results also indicated an optimum dosage of poly(DADMAC) as a pretreatment for the microparticle system. It is worth noting that high-shear treatment reduced, but did not eliminate the drainage benefit. Therefore, this is another case where the observations are consistent with an ability of fiber flocs to reform themselves after having been dispersed.

Conclusions

1. Fiber flocs formed as a result of sequential treatments with a high-charge cationic polymer, followed by a very-high-mass acrylamide copolymer were broken down irreversibly by intense hydrodynamic shear. The flocs formed again in the absence of high shear only to the extent characteristic of untreated fiber slurries. Essentially similar results were obtained with either cationic or anionic high-mass flocculants used as the final additive.
2. Varying the level of poly(DADMAC) pretreatment before cPAM had an insignificant effect on fiber flocculation. By contrast, aPAM was completely ineffective as a flocculant in the absence of the anchoring sites provided by the poly(DADMAC).
3. Fiber flocs formed as a result of micro-particle treatments showed the highest level of reflocculation of the systems tested, but only when there was a three-step addition sequence before application of intense shear. The first additive was poly(DADMAC), followed by cPAM, and finally colloidal silica. The strongest initial flocculation was at the approximate neutralization of the surface charges.

4. Though the intense hydrodynamic shear associated with 30-second exposure in a blender was sufficient to eliminate all or most fiber flocculation resulting from chemical treatment, in many cases it was not sufficient to disperse the fine particles and fillers. Papermakers can take advantage of this mechanism in cases where a flocculant is added upstream of a high-shear unit operation such as a pressure screen, making it possible to achieve satisfactory formation uniformity, as well as filler retention.

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Table 1. Effects of successive addition of low- and high-mass cationic polymers

DADMAC (low mass) level (%)	0	0	0.05	0.125
cPAM level (as-received, %)	0	0.1	0.1	0.1
Freshly Treated				
Viscometer reading, initial (%)	19.7	37.1	36.6	36.7
Light fluctuations, initial	0.11	0.28	0.30	0.27
Light fluctuations, after pumping	0.12	0.27	0.27	0.23
Viscometer reading, after pumping	21.0	28.6	26.5	25.3
Drainage time, after pumping (s)	39.0	24.0	24.0	28.0
Fiber pad wet mass (g)	6.5	4.2	4.2	4.2
Filtrate turbidity (NTU)	331	147	46	54
After Blender Treatment				
Viscometer reading (%)	19.3	20.2	19.6	23.4
Light fluctuations	0.12	0.11	0.13	0.09
Drainage time, after blender (s)	40.5	42	36	45
Fiber pad wet mass (g)	7.6	6.9	5.5	11.8
Filtrate turbidity (NTU)	344	349	50	59
Electrophoretic mob. ($10^8 \times \text{m}^2/\text{Vs}$)	-1.66	-1.80	-0.67	-0.94

Fig. 1. Effect of low-mass poly(DADMAC) dosage (actives basis) on viscometer output in case of fiber slurry samples subsequently treated with 0.1% cPAM (as-received basis). The arrow pointing to the vertical axis indicates the floc strength index in the case of untreated slurry (blank experiment).

Fig. 2. Effect of high-mass poly(DADMAC) alone on filtrate turbidity

Fig. 3. Effect of 0.05% anionic polyacrylamide (aPAM) (as-received basis) or the same amount of aPAM preceded by 0.05% low-mass poly(DADMAC) (actives basis) on viscometer output. The “delay” refers to the time of gentle stirring between the two chemical additions.

Fig. 4. Effect of aPAM and low-mass poly(DADMAC) plus aPAM on drainage time. See Fig. 3 caption for dosages.

Fig. 5. Effect of aPAM and low-mass poly(DADMAC) plus aPAM on filtrate turbidity. See Fig. 3 caption for dosages.

Fig. 6. Effects of three types of micro-additives, following treatment by 0.05% low-mass poly(DADMAC) and 0.1% cPAM, on viscometer output. Micro-additive dosages were 0.1% (actives) in the case of colloidal silica, 0.1% (as received) for the organic micropolymer, and 0.1% (actives) for bentonite. The arrow indicates the value of floc strength index in the case of a blank with no poly(DADMAC), cPAM, or micro-additive.

Fig. 7. Effect of poly(DADMAC) pretreatment level on the viscometer output of fiber slurries subsequently treated with cPAM (0.1%) and colloidal silica (0.1%).

Fig. 8. Effect of poly(DADMAC) dosage on drainage rate in the case of fiber slurry subsequently treated with 0.1% cPAM, followed by 0.1% colloidal silica. The arrow indicates the drainage rate in the case of a blank with no poly(DADMAC), cPAM, or micro-additive.