Fines Management for Increased Paper Machine Productivity

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ABSTRACT

Fiber fines present in papermaking furnish can have an adverse effect on the productivity of paper machines, especially at high fines levels and in products having high basis weight. The goals of this study are to compare the effects of different types of fine, fibrous material on the ease of water removal from paper and also to compare different strategies for the addition of a drainage-promoting additive. Two contrasting types of fiber fines were prepared from a southern U.S. bleached hardwood kraft pulp. Primary fines, consisting mainly of relatively short, "blocky" parenchyma cells, were obtained by classifying the unrefined pulp with a 100-mesh screen and collecting the fraction that passed through the screen. Secondary fines, consisting mainly of thin, flexible strands, were prepared by extensively refining the fraction that had been retained by the screen; then the refined fraction was classified again, using the same 100-mesh screen. Consistent with work done by others, fines tended to impede dewatering in a simple filtration test. Results of tests with a high-mass cationic polymer were consistent with the existence of at least two important mechanisms to account for the effects of fines on drainage. The adverse effect of primary fines on drainage could be partly overcome by adding a flocculant in such a way that the fines became attached to fibers, preventing the fines from moving through the fiber mat to points where they would obstruct drainage channels. The adverse effect of secondary fines on drainage could be more effectively overcome by treating them in such a way as to reduce their effective surface area. These findings suggest that addition of a flocculant to white water upstream of a fan pump may promote more effective release of water from paper machine webs in some cases.

INTRODUCTION

There can be little doubt that high levels of fine, fibrous material in papermaking furnish tend to make it more difficult to remove water during the formation process. For example, Gess [1991] and Wildfong *et al.* [2000] showed that resistance to dewatering increased nonlinearly with increasing fines content and with increasing basis weight. On many paper machines such resistance to water removal can be the limiting factor in the rate of production. Though papermakers can compensate for such effects by adding chemical dewatering aids [Yaraskavitch 1991], the molecular mechanisms by which these agents work are still poorly understood. In particular, there has been relatively little study of how dewatering chemical strategies can be selected to compensate for the effects of different kinds of fiber fines.

The economic impact of fines, due to their effect on dewatering and production rates, is expected to be most significant for paper grades that contain mechanical pulp, and also certain grades that contain recycled fiber [Woodward 1996]. Doshi [1998] enumerated many problems resulting from high fines levels in such grades; in conclusion he suggested that papermakers incinerate fines to recover their energy value. In this context it makes sense that any strategy designed for more effective utilization of fine materials should at least have a net value higher than the energy content of those fines.

Some of the best studies of fine materials in papermaking furnish have involved mechanical pulps; such pulps are widely used for newsprint and magazine production [Lindholm 1983; Wood *et al.* 1991; De Silveira *et al.* 1996; Luuko, Paulapuro 1999; Rundlöf *et al.* 2000]. Already in the 1950's Brecht and Klemm [1953] observed that groundwood fines can be separated into two contrasting classes, each with contrasting effects on papermaking operations and paper quality. A fraction called wood flour or "Mehlstoff," contributes bulk and opacity to groundwood sheets. A fraction of fine, fibrillar or mucilaginous material ("Schleimstoff") contributes to inter-fiber bonding.

Due to the complex shapes and broad particle size distributions in mechanical pulps it was decided to focus on a simpler type of furnish for the experiments described in this report. Hardwood kraft pulp, usually the major ingredient of printing paper, contains two main types of fiber fines. A component called "primary fines" consists of material already present in the wood and liberated by dissolution of lignin during the kraft cook. Primary fines in a typical southern U.S. hardwood species such as birch can comprise about 10% of the dry weight of the pulp that is produced [Smook 1992]. The words "secondary fines" have been used historically to refer to fine material that is produced by refining. In other words, these are the fragments torn or cut from fibers as they are repeatedly sheared and compressed in order to develop their ability to bond to each other when dried. Effects of fines from kraft pulps have been studied by Htun and De Ruvo [1978], Molina *et al.* [1984], Marton [1991], Fjerdingen and Houen [1997], and Mansfield and Saddler [1999].

Mechanisms to Explain Drainage Resistance

Three models will be considered here in order to account for the adverse effects of fine materials on the dewatering of paper. These will be called (a) the surface area model, (b) the choke-point model, and (c) the mat density model.

Surface area model: Consider the contrasting cases illustrated in Fig. 1 for dewatering of suspensions by filtration through a screen. In this simplified diagram the fibers and fines are represented by cross-sectional views. The fibers are pictured as if they were perpendicular to the plane of the figure. The central "empty" area of each fiber cross-section represents the lumen. In the right-hand image, fine particles are shown as smaller objects, but still with no attempt to accurately indicate their shape. According to Marton [1980, 1991] it is common for fines in papermaking furnish to absorb between 3 and 5 times as much polymeric material, per unit mass, compared to fibers. The high specific adsorption was attributed to higher surface area.

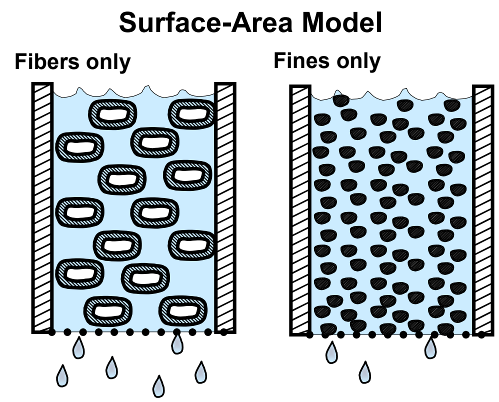

Fig. 1 –Idealized model to account for the effect of fines on drainage based on the different surface areas of fine materials, relative to fibers.

The relationship between solid surface area and resistance to flow through a mat has been studied extensively, especially with regards to packed-bed filtration processes [Lindsay 1994]. These studies show that the superficial velocity through such a packed bed or mat tends to follow Darcy's law,

$$v_{\text{superficial}} = K\,\Delta P / (\,\mu L\,)\,, \tag{1}$$

where K is the permeability (units = length squared), ΔP is the pressure difference across the pad or mat, μ is the shear viscosity, and L is the thickness of the pad or mat. The superficial velocity is the flow rate divided by the area, neglecting the packing material.

It has been shown that the value of the permeability coefficient K is consistent with the Kozeny-Carman equation,

$$K = (1 / 5.55\, S_0^{\,2}\,) \text{ x } (1 - \alpha\, c\,)^3 / (\alpha\, c\,)^2\,, \tag{2}$$

in which S_0 is the hydrodynamic surface area per unit volume, α is the effective volume per unit mass, and c is the consistency (mass of solids per volume of sample).

Lindsay extended the Kozeny-Carman model to account for the fact that some water in a fiber mat may not be readily accessible to flow [1994]. For instance, it would not make sense to include water within fiber lumens in a model to predict resistance to flow through such a mat. Also, dead-end pores could be excluded. However, it was found that as much as 90% of water external to the fibers themselves was set in motion during flow through experimental pulp mats.

The Kozeny-Carman model can be applied to cases of fines-containing furnish, at least as an approximation, if one makes some simplifying assumptions. First, one can neglect effects due to the detailed structure of the fibrous mat. Second, one can assume linear additivity of contributions to drainage resistance due to the fibers and the fines. Wei *et al.* [1996] showed that this kind of model could account for dewatering resistance in a simple filtration process, such as in the formation of handsheets. One of the achievements of this model was to show the relationship between the pad density, c, as a function of location in a forming handsheet or freeness pad. Related models also were able to account for the location of fine particles in fiber mats formed by simple filtration [Maunier, Ramarao 1996].

Though the Kozeny-Carman model is not the only way to account of resistance to dewatering during paper manufacture, it may provide insight into the role of fines, as well as possible ways to promote dewatering in the presence of fines. The model predicts, first of all, that drainage resistance should depend on the specific surface area and the local density of a fiber mat. By geometrical considerations, the specific surface area of solid, non-porous particles, having uniform shape, should be inversely proportional to their length or diameter. Consistent with this expectation, Patel and Trivedi observed a larger adverse effect on dewatering with decreasing size of fine particles [1994].

A possible wet-end chemical strategy that is consistent with the Kozeny-Carman model is to minimize the adverse effects of fines by agglomerating them together into larger particles. As shown by Wood *et al.* [1991] and Blechschmidt *et al.* [2000], the hydrodynamic surface areas of fine materials can be characterized by a sedimentation method; these may involve either a hydrocyclone or centrifugation as an alternative to simple gravity sedimentation. Early work related to the flocculation of fiber fines was reported by Das and Lomas [1973], including the idea of using a highly charged cationic polymer to reverse the surface charge of a portion of the fines, then using those "superfines" to collect other fines into larger agglomerates. Related work was reported by Krogerus [1993]. Gavelin [1988] developed similar ideas as a strategy for more effective retention of mineral fillers.

Enzyme treatment provides another strategy to decrease the hydrodynamic surface area of fibrous materials. Eriksson, Heitmann, and Venditti [1997] showed that moderate treatment of furnish with a cellulase significantly increased the freeness of old corrugated container (OCC) furnish without hurting the strength of the resulting paperboard. Work reported by Jackson, Heitmann, and Joyce [1994] showed that the enzymes preferentially reacted with fine and colloidal materials in the furnish due to their relatively high specific surface areas. Excessive enzymatic treatment, however, can have the undesired effect of increasing production of fines during subsequent refining [Seo *et al.* 2000].

Choke-Point Model: A deficiency of the "surface area model" just described is that it does not account for structural features of a fibrous mat. As shown by Lappan *et al.*, flow through a fibrous mat is expected to depend on the nature of flow channels and any restrictions in these channels [1996]. As illustrated in Fig. 2, a key assumption of the choke-point model is that at least a portion of the fine particles are initially free from any fiber surfaces. According to the view shown in Fig. 2 one expects relatively little effect of such fines on dewatering at the very start of a filtration process.

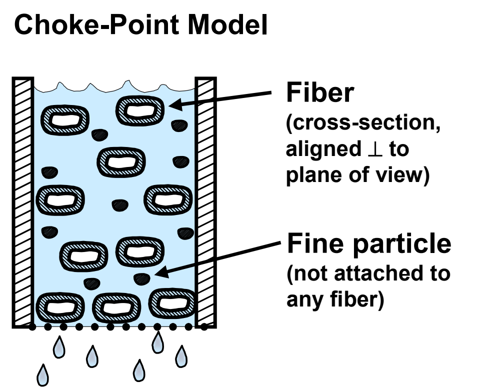

Fig. 2 – Starting condition and a key assumption of an idealized model in which fines move to block choke points.

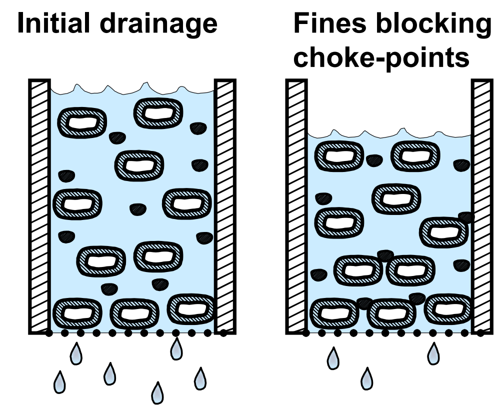

Fig. 3 – Illustration showing why motion of fines toward choke points in a fiber mat is expected to decrease the drainage rate.

Figure 3 shows an idealized view of an altered situation, after a certain amount of filtration dewatering has occurred. Note, in the right-hand view, that some of the fine particles have migrated through the forming mat of fibers, and they have become stuck at points where they obstruct flow [Patel, Trivedi 1994]. The flow of water during drainage is expected to favor build-up of fines at precisely those locations where their presence is least advantageous for further dewatering.

Evidence suggesting that the choke-point model plays a significant role during paper manufacture comes from studies that considered effects of basis weight and high fines levels on drainage [Gess 1991; Wildfong *et al.* 2000]. These studies showed that resistance to dewatering, in the presence of high levels of fines, increased non-linearly with basis weight. Such results are consistent with the increased entrapment of fines in parts of the forming mat that exist for the longest time and become most dense under the hydrostatic pressure [Wei *et al.* 1996]. Further support for the choke-point model comes from the work of Lindholm [1980]; it was found that conditions leading to relatively poor retention of fines yielded the largest resistance to drainage. The choke-point model also can explain why a pulsating drainage apparatus, partly simulating what happens during commercial paper production, can greatly reduce the effect of fines on dewatering [Britt *et al.* 1986]. Pulsation can have the effect of washing fine materials from the fiber mat, especially in the layers nearest to the forming fabric [Räisänen, Paulapuro, Karrila 1995; Zeilinger, Kline 1995].

Though it would be difficult to accurately model such effects, the idealized choke-point model also suggests that the shapes and particle sizes of fines ought to play significant roles relative to blockage of flow channels. On the one hand, if a “fine” were too large or too long to be able to change its relative position in the fiber mat, then one would expect it to act like any other fiber during dewatering. On the other hand, if a “fine” is extremely small, then it is likely that it simply passes through all of the channels in the wet mat and leaves with the filtrate or “white water.” The rules related to the size of particles are expected to be different for long, fibrillar fines, compared to fine particles having compact shapes.

To the extent that a choke-point model adequately explains effects of fines on dewatering, one promising approach is to attach fine particles to the fibers by means of retention chemicals [see Scott 1986]. The idea that retention aids often promote dewatering of paper already has been well established [Wegner 1987; Allen, Yaraskavitch 1991]. The classic work by Britt [1973] established that high-mass polyelectrolytes can flocculate fines onto fibers and/or agglomerate them together sufficiently [see Davison 1982] that they cannot pass through a fine screen. Since the choke point model requires relative movement of fines through the fiber mat, it follows that the effect can be overcome by binding those fines in a way that prevents such migration through the mat.

Mat Density Model: Work reported by De Silveira *et al.* [1996] showed that the location of fines in a mat of paper can affect its overall structure and also its strength and light scattering characteristics. In principle, the fines can either "bridge" or "fill" spaces between fibers within the mat of paper being formed. An idealized view of the "pad density model" to explain the effect of fines on dewatering is shown in Fig. 4. The left-hand part of the figure shows the limiting case in which the fine particles act as spacers between adjacent fibers. In this way they may be able to inhibit densification of the fiber mat and preserve relatively large flow channels through the mat during at least the initial phase of the dewatering process. The right-hand view considers the alternative limiting case in which all of the fines slide into spaces between the fibers, yielding a denser mat.

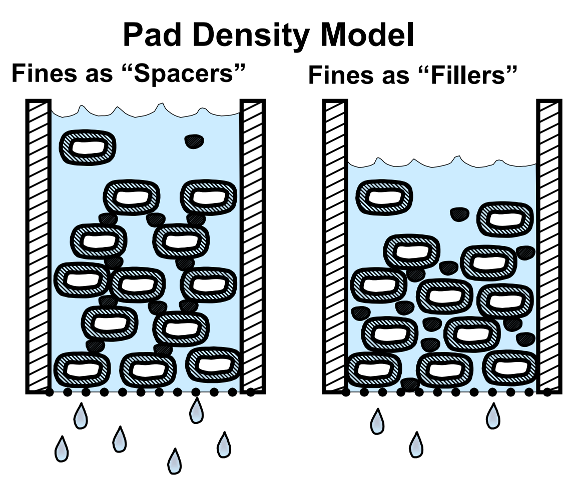

Fig. 4 – Illustration of how fines may act as either spacers or fillers in a wet mat of fibers, thus affecting its density and permeability.

Sampson [1997] considered other factors that may affect sheet structure and drainage. In particular, the effective size of channels in a fiber mat is expected to be related to the uniformity of the mass distribution. On the one hand, flocculation of fibers is expected to make the mat less uniform. On the other hand, a healing process may occur to the extent that flow draws materials toward thin areas of the mat.

In principle, one way that papermakers can control the structure of a fiber mat is to change the tendency of the surfaces to cling to each other when they contact. This can be done with chemicals that neutralize surface charges or allow for the formation of polymeric bridging between surfaces. Lindström [1989] has suggested that such chemical interactions are responsible for the somewhat more "open" structure of paper webs that have been treated with microparticle-type dewatering chemicals. The effect appears to be closely related to the better-known subject of sedimentation volumes [Kline 1967]. According to this mechanism, a low-density structure results if particle "stick" in the positions in which they first collide. Alternatively, a high-density structure results if there is net repulsion between the surfaces, as in the case of like-charged particles with no polymeric bridging. In the latter case the particles are able to slide past each other and adopt a dense structure. Because sliding may play a role in this mechanism, it is also worth considering a possible relationship between pad density and the friction between the wet surfaces of fibrous materials [Zauscher 2000], and also the effects of chemicals on network-forming tendencies of fiber suspensions [Swerin *et al.* 1996; Hubbe 2000]. It is worth noting that such chemical effects are not limited to systems containing fine materials, but are expected to affect the structure of fines-free paper as well.

EXPERIMENTAL

Materials

Water: Deionized water was used for the experiments, except that tap water was used for initial disintegration and fractionation. Sodium sulfate was added to achieve an electrical conductivity of 1043 μS/cm in the water used for preparation of suspensions of fiber fines, fibers, and mixtures of the two.

Fibers: The fines-free fiber fraction used throughout this work was obtained by the scheme shown in Fig. 5. The fiber source consisted of multipurpose office paper from International Paper Co., bearing the brand name Relay MP®. The labels stated that the paper contained at least 30% of post-consumer recycled content. Batches of 43 grams each of copy paper were subjected to 3000 revolutions of disintegration (TAPPI method T205). Sub-batches consisting of about 10 g oven-dry solids (one-quarter of the amount in the disintegrator) were separately processed using the final agitated compartment of a Bauer-McNett fractionator, using only a 100-mesh screen. Fines were collected in a centrifuge bag having a nominal screen size of 150-mesh; these were set aside for later, optional use, mainly for comparison with the effects of other kinds of fine materials. The fiber fraction was recovered after ten minutes of running the classifier. For convenience, the fibers were formed into thick handsheets, which were stored in their wet state.

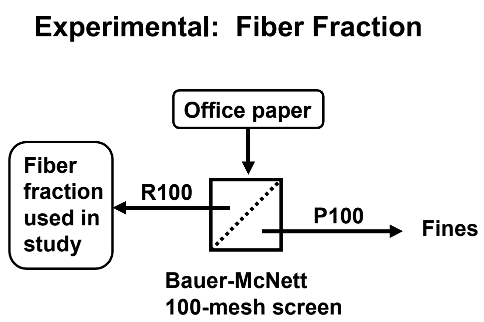

Fig. 5 – Fractionation scheme for obtaining the fibers used throughout this work, plus one of the fines samples.

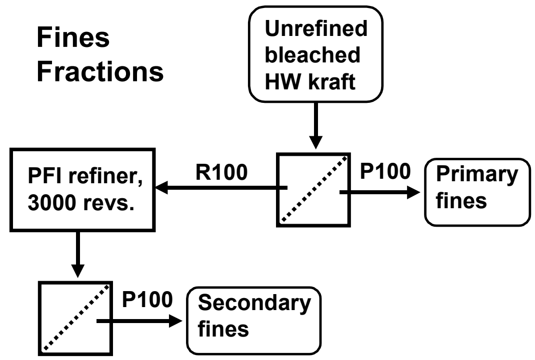

Fig. 6 – Fractionation scheme for obtaining the primary and secondary fines from bleached hardwood kraft pulp.

A master batch of fines-free fibers from the office paper was prepared. The consistency was 0.164%. The conductivity was adjusted to 1043 µS/cm by addition of sodium sulfate.

An alternative procedure also was used to collect fines from certain batches of office paper. Instead of using the centrifuge bag, the P100 ("passing 100-mesh") fraction was collected in a pair of 30-gallon rolling containers. These containers were left undisturbed for four days. The supernatant solution was removed by siphoning. The fines slurry was then placed in a large beaker and allowed to sediment for an additional four days, and further supernatant solution was removed. The final consistency was 1.77%.

Primary Fines: Unrefined, bleached southern U.S. hardwood kraft pulp was used as the source of primary fiber fines. The scheme for obtaining these fines is illustrated in Fig. 6, as shown on the right-hand side of the figure. The unrefined hardwood pulp was disintegrated in the same way as the office paper; then it was fractionated in the last compartment of the Bauer-McNett device. Material that passed the 100-mesh screen was collected in centrifuge bags. These were allowed to gradually drain.

Secondary Fines: The hardwood fibers obtained by the first fractionation just described were thickened by forming them into handsheets. The wet pulp was then diluted with deionized water to a consistency of 10%. Approximately 30 grams, oven-dry basis, were refined with 8000 revolutions of a PFI mill (TAPPI Method T 248). Fines were collected by the same method as before, using a 100-mesh screen in the final compartment of a Bauer-McNett device. The P-100 fraction was collected in centrifuge bags.

Flocculant: The cationic acrylamide copolymer used as a flocculant was Percol® 455 from Ciba Specialty Chemicals. The percentage of cationic monomer groups, by mass, is approximately 3%, and the intrinsic viscosity is approximately 11 dl/g. The rationale for using this type of polymer was to create strong, relatively irreversible attachments between or among selected fractions of solid materials and to avoid confounding the results with large changes in the charge characteristics of the surfaces.

Though it is usual to also consider the use of highly charged cationic additives such as alum, polyaluminum chloride (PAC), polydiallyldimethylammonium chloride (poly-DADMAC), or polyethylenimine (PEI), preliminary results shows that such treatments were not suitable for the fiber slurry that was used in the present work. Streaming current titrations showed that colloidal materials from the repulped office paper already had a weak positive charge. Consistent with this finding, preliminary tests involving the addition of cationic materials showed no benefits in terms of dewatering rates.

Characterization Methods for Fines and Fillers

Characteristics of fibers and fines fractions were evaluated with a Fiber Quality Analyzer (FQA), supplied by OpTest Equipment, Inc.

The hydrodynamic specific surface of fines was estimated by observing the rate of free settling in a highly dilute suspension. The same dilute sodium sulfate solution was used as the supporting medium. The consistency of fines during these tests was approximately 0.05%. The nominal density of cellulosic material was taken to be 1.55 g/cm^3 for purposes of determining an effective hydrodynamic surface area or equivalent diameter according the Stokes equation,

$$D_{\mathrm{hydro}} = [\ 18\, v\, \mu / (g\, \Delta\rho)\ ]^{0.5}\ , \tag{3}$$

where v is the terminal settling velocity, μ is the shear viscosity, g is the acceleration of gravity, and $\Delta\rho$ is the difference in density of the solids relative to the suspending medium. The effective value of the hydrodynamic specific surface area was computed from the Stokes diameter according to the equation,

$$S_0 = \text{(area of sphere) / [(volume of sphere) x density)]} \tag{4}$$

$$= 4\, \pi\, R^2 / [\ 4/3\, \pi\, R^3\, \rho\ ] = 3 / [\ \rho\, R\ ] = 6 / [\ \rho\, D_{\mathrm{hydro}}\ ]$$

Photographs were obtained with a light microscope at initial magnifications of either 50x (5x objective) or 200x (20x objective). Images were captured with a video camera.

Dewatering Tests

Simple filtration by gravity was carried out by placing 250 of suspension in a Millipore® filtering apparatus, fitted with a 150-mesh stainless steel screen. The circular open area of the screen had a diameter of either 21 mm (most of the tests) or 41 mm (for tests involving the sequence of addition of the flocculant). Drainage times were determined by starting a stopwatch upon addition of furnish to the filter apparatus and stopping it when the level reached the 50 ml mark.

The turbidity of filtrate from gravity drainage tests was evaluated with a DRT-15CE turbidimeter supplied by HF Scientific.

Response to vacuum dewatering was determined by redispersing the entire 250 ml of sample material, including what was used for turbidity evaluation. This suspension was placed in a device fashioned from a bottomless plastic graduated cylinder fitted into a small Büchner funnel. A circular piece of 150-mesh screen was placed over the 42 mm diameter perforated surface of the funnel. House vacuum (max 590 mm Hg) was applied 10 seconds after adding the suspension to the device. Filtration typically required about 3 seconds. The final vacuum was recorded after 10 seconds of vacuum application. The final moisture was determined by extracting the fiber pad, weighing it, then reweighing it after drying at 105 ^{o}C.

Sequence of Addition of Cationic Flocculant

The scheme for experiments involving cationic flocculant is shown in Fig. 7. Each experiment used 250 ml of 0.164% consistency fiber fraction from office paper. The amount of fines was adjusted in different cases to achieve approximately the same overall effect on dewatering in the absence of flocculant. In the case of primary hardwood fines, 8 ml of 3.94% consistency slurry were added to the mixture. In the case of secondary hardwood fines, 8 ml of 1.85% consistency slurry were added to the mixture.

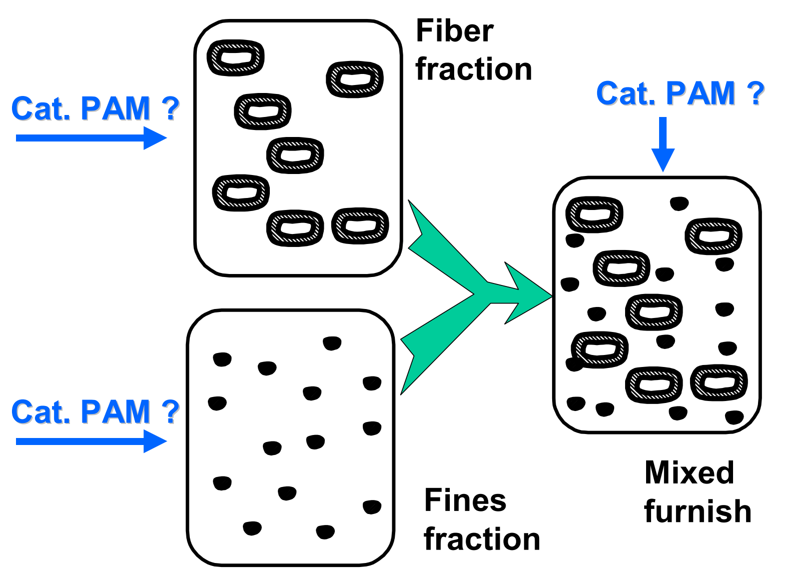

Fig. 7 – Scheme for addition of cationic flocculant to different fractions, or to combined mixtures of fibers and fines.

The amount of cationic polymer was kept the same in all cases in which it was applied, 0.5 ml of 0.1% solution. This amount of polymer corresponds to 0.069% treatment by mass in cases involving primary fines and 0.090% in cases involving secondary fines. Mixtures were stirred vigorously for ten seconds with a spatula after addition of each new component, including either fibers, fines, or chemical.

RESULTS AND DISCUSSION

Characterization of Fibers and Fines

Length analysis: Table 1 summarizes length-related properties of the fines-free fibers and of the various samples of fiber fines. The data are length-weighted quantities from the FQA instrument.

Table 1 – Length-Related Properties of the Fiber and Fines Fractions

Fraction	Fines Content (%)	Mean Length (mm)
Fibers from office paper, R100	0.6	1.64
Primary fines from HW, P100	77.5	0.18
Secondary fines from HW, P100	14.9	0.79
Fines from office paper, P100 (1)	29.1	0.80
Fines from office paper, P100 (2)	50.7	0.59

Notes: (1) Method 1 = fines collected in 150-mesh centrifuge bag; (2) Method 2 = fines collected by setting and siphoning of supernatant solution.

It is worth noting that the FQA test showed only about 15% of "fines" in the P100 fraction from the highly refined hardwood from which primary fines had been removed. Indeed, microscopic images (see later) confirmed that the PFI refining treatment did not result in extensive cutting of the fibers, even though they became flexible enough to act like fines with in terms of their ability to pass through the screen [Gooding, Kerekes 1989]. These results are consistent with experience showing that the PFI device is relatively low in its intensity of refining action.

Sedimentation: Table 2 shows results of sedimentation tests of untreated fines fractions. Repeat measurements showed high variability, with a tendency for the settling rates to increase with time. This effect is tentatively attributed to agglomeration of particles in the course of the sedimentation tests.

The higher hydrodynamic specific surface area of the secondary fines, compared to the primary fines, helps to explain various observations reported by others. For instance, in the case of kraft pulps Lobben [1977] reported that the secondary fines contributed much more to inter-fiber bonding than did the primary fines fractions. Fjerdingen and Houen [1997] reported that secondary fines, even when produced from recycled kraft furnish, were more highly swollen than either primary fines or recycled fines of all types. In the case of mechanical pulps the secondary fines have been described as being more fibrillar, having a stronger adverse effect on dewatering, and having a higher beneficial effect on inter-fiber bonding [Brecht, Klemm 1953; Waterhouse, Omori 1993; Luuko, Paulapuro 1999].

Table 2 – Results of Sedimentation Tests		
Fraction	**Equivalent spherical diameter (μm)**	**Hydrodynamic specific surface (cm^2/g)**
Primary fines from HW, P100	44	430
Secondary fines from HW, P100	18	1050

.

Photographs: Figures 8 and 9 show the fiber (R100) and fines (P100, method 1) fractions, respectively of the repulped office paper. As can be seen partly in Fig. 8, the fibers length distribution tended to be bimodal, with many fibers having lengths near to 1 mm, and many others having lengths in the 2-3 mm length range. Such a distribution is consistent with the presence of both hardwood and softwood kraft fibers.

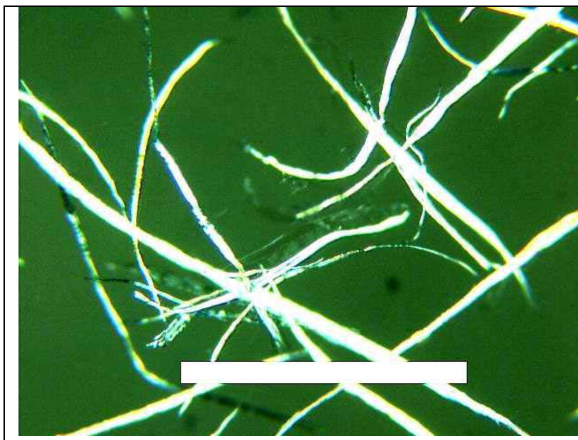

Fig. 8 – Fiber fraction (R100) from repulped office paper. Bar = 1 mm.

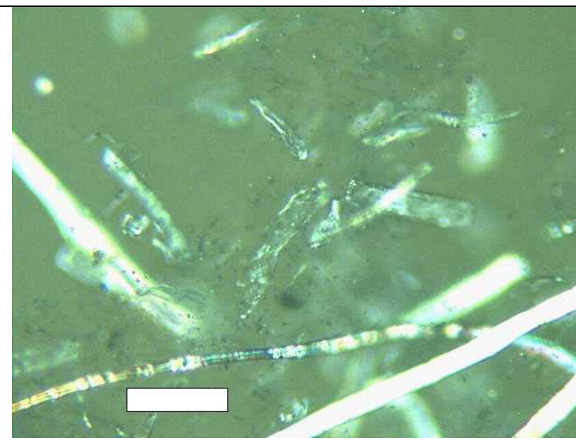

Fig. 9 – Fines fraction (P100, method 1) from repulped office paper. Bar = 100 μm.

The fine material in the P100 fraction of the office paper (method 1), as shown in Fig. 9, appeared to contain a mixture of materials, including parenchyma cells (see later), fiber fragments, mucilaginous material, and possibly some mineral filler. In addition to the fine material, observations at lower magnification showed that some fibers, having lengths in the neighborhood of 1 mm, were present in the P100 fractions from the office paper. Since method 1 involved collection of fines in centrifuge bags, it is to be expected that much of the mineral filler could escape through openings in the 150-mesh bag.

Additional photographs of P100 samples from the same office paper, but collected by sedimentation (method 2) were very similar to Fig. 9. However, the method of collection is well suited to saving the mineral content, in addition to the fiber fines. The higher value of fines and the lower mean length shown in Table 1 for method 2 are also consistent with the presence of more mineral, and possibly more fine colloidal material from the office paper, compared to method 1. The P100 fractions from bleached hardwood kraft pulp are shown in Figs. 10 and 11. The relatively compact shapes of the particles shown in Fig. 10 are consistent with what is expected for parenchyma cells, *i.e.* wood cells involved in food storage and in transportation of materials radially into the tree.

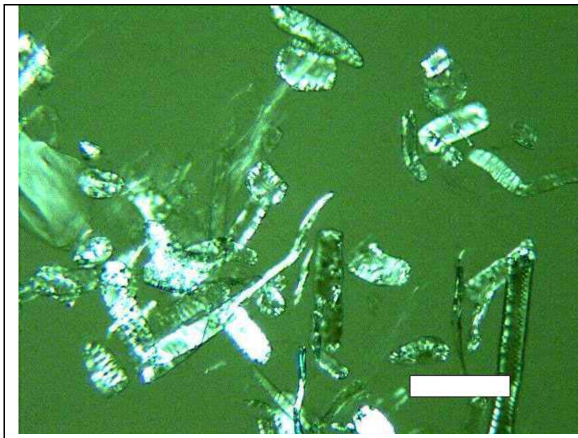

Fig. 10 – Primary fines (P100) from un-refined, bleached hardwood kraft pulp. Bar = 100 µm.

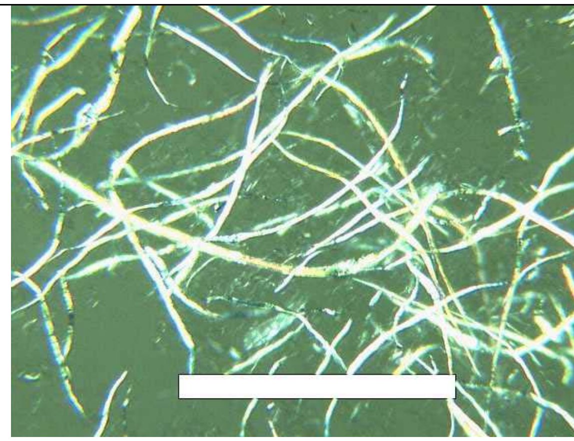

Fig. 11 – The P100 fraction, "secondary fines," from refined hardwood kraft after removal of primary fines. Bar = 1 mm.

Consistent with data in Table 1, Fig. 11 shows a high proportion of intact fibers in the P100 fraction of highly refined hardwood kraft pulp. Though it is possible that some of the objects shown in the photograph are either split fibers or cut fibers, such damage is not obvious. It is to be expected that the more flexible nature of highly refined fibers allows them to pass more easily through a screen of fixed size [Gooding, Kerekes 1989]. It is interesting to note that the equivalent diameter shown in Table 2 for this sample is in the same range as the observed fiber thickness, *i.e.* of the order of magnitude 18 µm.

Effects of Fines on Dewatering

Office paper fines: Figures 12 and 13 show consequences of reconstituting office paper furnish at different levels of fines by recombining the separated fractions. As shown in Fig. 11, the drainage times increased markedly with increasing fines content, especially when fines were present at levels above about 7%. A fines content of about 17% was enough to double the drainage time, compared to mats formed from fines-free fibers.

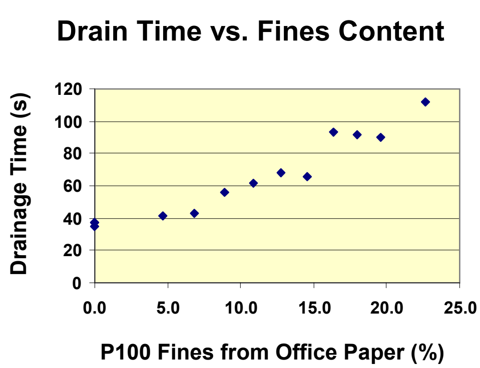

Fig. 12 – Effect of fines from office paper on dewatering rates through mats formed from fibers taken from the same source.

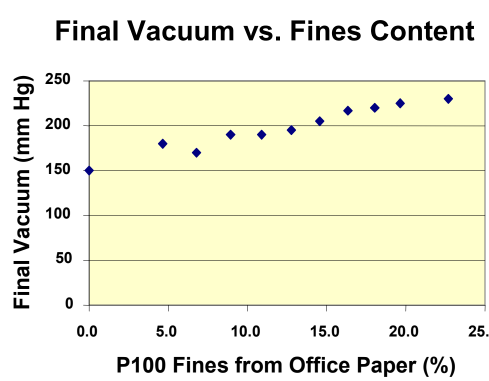

Fig. 13 – Effects of fines from office paper on the vacuum measured at the end of a vacuum dewatering test.

As shown in Fig. 13, the observed final vacuum levels also increased with increasing fines content. In other words, fines increased resistance to flow of either water or air through wet or moist fiber pads, respectively.

Various types of fines compared:

As shown in Fig. 14, the P100 fraction from the highly refined kraft pulp had a much larger negative effect on dewatering, compared to the other types of fines considered. If one compares results at any given value of fines content, then the "secondary fines" (plotted as circles) appeared to have about three times the impact on drainage time as the same amount of primary fines (square symbols plotted). Within experimental error, this ratio agrees with the ratio of hydrodynamic specific surface areas shown in Table 2. In agreement with previous work [Gess 1991; Wildfong *et al.* 2000], the resistance to flow increased in a non-linear fashion with increasing fines content for all of the type of fines evaluated.

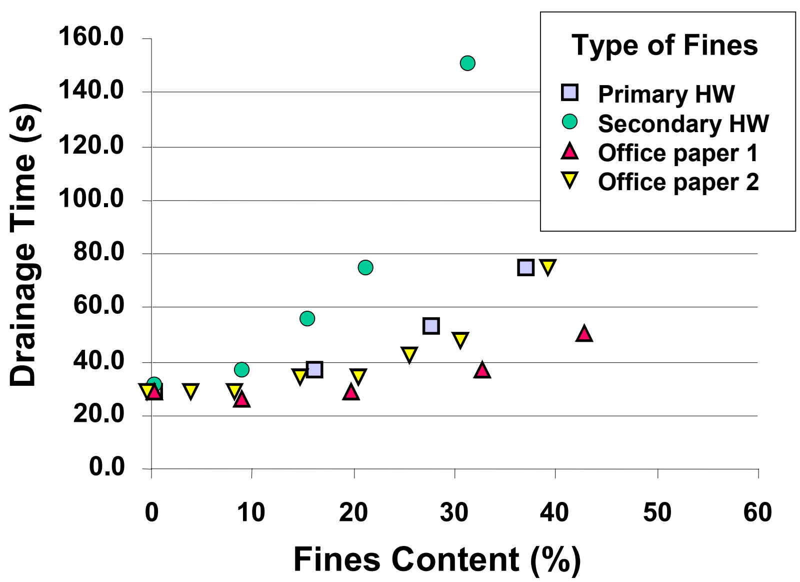

Fig. 14 – Effects of increased amounts of different types of fines on drainage through mats formed mainly from the fiber fraction of repulped office paper.

Results of turbidity tests suggest that different mechanisms may be involved in the case of primary fines *vs.* secondary fines in the absence of retention aid treatment. A turbidity of 8.2 NTU was observed in filtrate collected from a furnish that contained approximately 44% primary fines. By contrast a turbidity of only 3.8 NTU was observed in filtrate collected from a furnish containing approximately 26% secondary fines. Since the light scattering abilities of the two kinds of fines were similar, these results indicate a much lower retention efficiency of the primary fines. By contrast, few of the secondary fines escaped into the filtrate. These results are consistent with a model in which the primary fines are able to migrate, to a greater extent, through a wet mat of fibers.

Addition Sequence of Cationic Flocculant

Photographs: As shown in Figs. 15 and 16, treatment with high-mass, low-charge cationic flocculant caused pronounced agglomeration of fines fractions obtained from hardwood pulp. Figure 15 shows that the primary fines tended to bunch together in somewhat random orientations. Figure 16 indicates a tendency toward alignment in the case of the P100 fraction from highly refined hardwood.

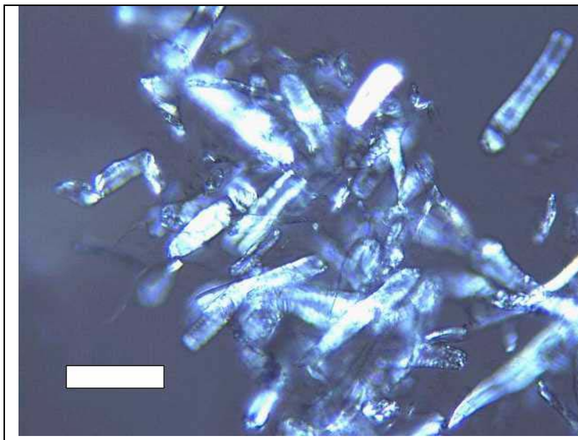

Fig. 15 – Agglomerate of primary fines resulting from treatment with cationic flocculant.

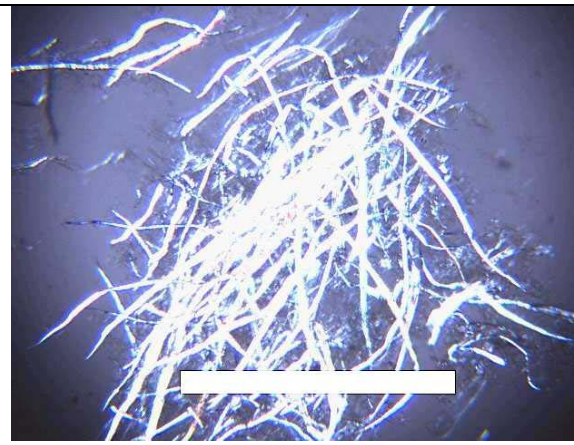

Fig. 16 – Agglomerate of secondary fines resulting from treatment with cationic flocculant.

Sedimentation: Table 3 shows corresponding results for sedimentation tests of these same two fines fractions, following polymeric treatment. These results show a significant change only in the case of the secondary fines, which settled much more rapidly after polymeric treatment. The hydrodynamic specific surface area fell by a factor of about three, compared to the value shown in Table 2. By contrast, treatment of the primary fines with cationic flocculant did not decrease the hydrodynamic specific surface area.

Table 3 – Results of Sedimentation Tests Following Treatment by Flocculant

Fraction	**Equivalent spherical diameter (μm)**	**Hydrodynamic specific surface (cm^2/g)**
Primary fines from HW, P100	42	460
Secondary fines from HW, P100	51	380

Dewatering rates: The pairs of histogram bars shown in Figs. 17 and 18 represent replicate experiments. As shown in Fig. 17 for primary fines, addition of cationic flocculant in any of the three modes – either to the combined furnish, to the fines only, or to the fibers only – resulted in a marked decrease in the time required to drain 200 ml of filtrate. However, addition of the flocculant to the fiber fraction appeared to be somewhat less effective than either of the modes involving addition of flocculant to a slurry that contained the fines (with or without fibers).

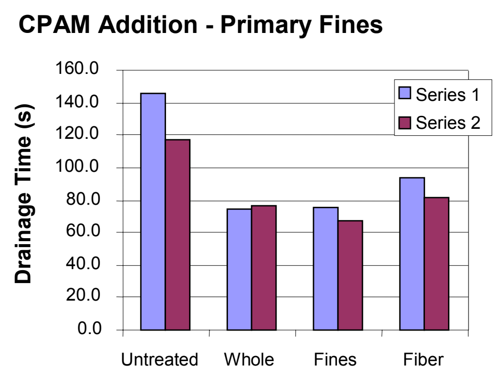

Fig. 17 – Drainage of systems involving primary fines, depending on the mode of addition of cationic flocculant.

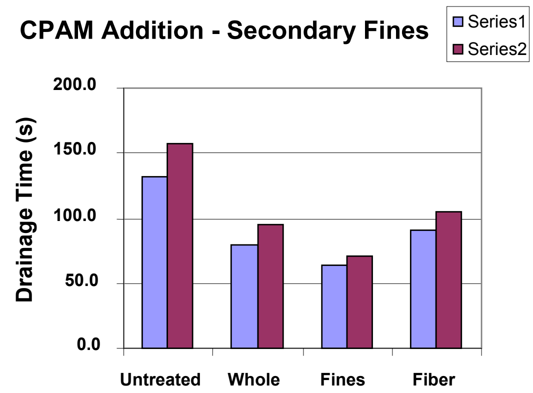

Fig. 18 – Drainage of systems involving secondary fines, depending on the mode of addition of cationic flocculant.

As shown in Fig. 18, in systems containing secondary fines the most rapid drainage was obtained by addition the flocculant to the fines fraction. This mode of addition was more effective than addition of the polymer to the whole furnish, and much more effective than its addition to the fiber fraction.

Practical Considerations

Based on results such as those shown in Fig. 18, a papermaker ought to be able to achieve improved drainage performance in some cases by selecting which component of the furnish to treat with flocculant. In practice such choices involve selection of addition points for a flocculating polymer, *i.e.* a retention aid. The usual practice is to add retention aid to the combined furnish, often just after or just before a pressure screen. But the present results suggest that there may be cases where it could be advantage to add some flocculant to the stream of returning white water, before it is used to dilute the thick-stock fiber slurry at a fan pump. Alternatively (though the present results do not support such a strategy), one could consider adding retention aid at a point before addition of certain fine material, as in the case of filler that may be added to thin stock.

Let's assume that someone decides to inject additional retention aid before a bend in the large pipe between the white water silo and the fan pump. A likely consequence of such an "early addition" strategy is a reduced overall efficiency of chemical use in terms of achieving given levels of first-pass retention. As discussed by Hubbe and Wang [2002], the resulting loss in efficiency is expected to be mainly due to the increased amount of hydrodynamic shear to which such polymers and agglomerated materials will be exposed. Further loss in efficiency can be due to the passage of time, allowing for adsorbed retention aid molecules to adopt flatter adsorbed conformations. Fortunately, flocs composed primarily of fine particles are expected to tolerate the application of shear much better than, say, fiber flocs [McKenzie 1968; Hubbe 1985, 1986].

Some other things to worry about if one is considering implementation of a whitewater flocculation scheme are as follows:

- On a given paper machine there might not be a tap available for injection of another additive to returning white water, especially at a location sufficient far from the fan pump as to allow good mixing before the streams are combined. In many cases the white water chest or silo is immediately adjacent to the main fan pump where stock dilution takes place.
- If retention aid continues to be added at a "regular" location, in addition to white water injection, then the complexity of the treatment system will be increased.
- If, on the contrary, one were to treat *only* the white water with retention aid, then one would, in effect, be treating only a portion of the total fines in the system on each pass. Fines entering with the thick stock fiber streams would not be directly treated. This is analogous to the system considered by Das and Lomas [1973]. A lower chemical efficiency, in terms of retention, would be expected.
- Through agglomeration of fines might be good for dewatering in some cases, it is not yet known how the treatment will affect strength properties. Studies have shown a relatively large contribution of secondary fines to strength development, with the greatest contributions due to those fines having the greatest tendencies to inhibit drainage [Brecht, Klemm 1953; Lobben 1977; Htun, De Ruvo 1978; DeSilveira *et al.* 1996].
- Likewise, agglomeration of fines might possibly have adverse effects on certain end-use properties, *e.g.* dusting, printing, curl, *etc.* Unfortunately, such effects usually can be determined only by commercial-scale trials.

Finally, it is worth noting briefly some other factors related to paper machine efficiency and effects of fines materials that have been neglected in the present analysis. It would make sense to focus more research attention in some of the following areas:

- Fines often contain disproportionate levels of pitch-like materials. These materials are often involved in deposit problems, spots, and holes or breaks in paper products. Recent work by Rundlöf *et al.* [2000] showed that hydrophobic substances in the fines fraction of mechanical pulp can have a large adverse effect on strength.
- Kufferath [1983] showed that interactions between the furnish and the surfaces of various kinds of forming fabrics can have significant effects on dewatering rates. In particular, slow drainage is expected if fibers or fines are able to "droop" into depressions in the forming fabric. These results suggest that improvements can be achieved by varying the stiffness of various furnish components or the colloidal forces that may help hold them together as a mat during paper formation.
- Youn and Lee [2002] showed recently that certain fines can markedly reduce the flocculation tendency of stock suspensions. To the extent that this effect is

important in a given situation, efforts to remove or agglomerate fines run the risk of hurting formation uniformity.

- Work reported by Britt, Unbehend, and Shridharan [1986] showed that the adverse effects of fines on drainage is greatly reduced if pulsations in pressure are applied during dewatering. Such effects are expected to be especially important in light weight grades and in cases were relatively strong washing forces are exerted by hydrofoils or forming blades. Related work is under way in our laboratory.

CONCLUSIONS

1. Idealized experiments in the laboratory showed marked differences in dewatering rates of kraft furnish, depending on the nature and levels of fine materials. Secondary fines, produced during refining of hardwood kraft, had a greater negative effect on gravity drainage than primary fines collected from the unrefined hardwood furnish.
2. It was possible to increase dewatering rates by addition of a flocculating chemical, *i.e.* a retention aid. Results depended on the sequence of addition. In the case of secondary fines, the most promising results were obtained when the flocculant was added to the fines fraction before it was combined with the fibers.
3. Results appeared to be explainable in terms of two, or possibly three idealized mechanisms to account for the effects of fines on dewatering.
    - A model based on hydrodynamic surface areas agreed with observed effects of different samples of fine materials on drainage. The same model also was able to account for the fact that treatment of secondary fines with flocculant decreased their hydrodynamic surface area and also yielded the largest relative increase in the rate of drainage.
    - A model based on blockage of choke points in the fiber mat channel structure was consistent with the relatively lower retention of primary hardwood fines, especially in the absence of retention aid. Also, addition of flocculant either to the mixed furnish or to the primary fines promoted dewatering effectively, consistent with the explanation that fines were prevented from migrating through the sheet. Turbidity test results also agreed with this explanation.
    - No tests were conducted specifically to support or rule out a third likely contributing mechanism involving changes in the density of the wet mat of fibers. Future work involving evaluation of yield stress of fiber suspensions and friction between wetted surfaces of fibers could help to show whether control of interactions between fines and fibers can be used as a strategy to produce more "open" wet mats of paper, offering larger channels for dewatering.

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