REVIEW OF FACTORS AFFECTING THE RELEASE OF WATER FROM CELLULOSIC FIBERS DURING PAPER MANUFACTURE

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The ease with which water is released from cellulosic fiber material during the manufacturing of paper can affect both the production rate and the consumption of energy during the manufacturing process. Important theoretical contributions to dewatering phenomena have been based on flow through packed beds of uniformly distributed fibers. Such descriptions are able to explain why resistance to dewatering increases as a function of the hydrodynamic surface area of fibers. More recent studies have demonstrated a critical role of finely divided matter. If the fines are unattached to fibers, then they tend to move freely through the fiber mat and plug channels in the paper web during the dewatering process. Dewatering also is affected by the deformability of cellulosic fibers and by whether the fibers easily slide past each other, thereby forming a dense mat. By emphasizing the role of fine matter, colloidal forces, and conformability of cellulosic materials, one can gain a more realistic understanding of strategies that papermakers use to enhance initial drainage and vacuum-induced dewatering.

Keywords: Dewatering, Drainage, Freeness, Fines, Water retention value, Kozeny-Carman, Choke-point mechanism, Mobility of fines, Sheet sealing, Sediment volume

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INTRODUCTION

The removal of water from cellulosic fibers and other materials in the wet web constitutes the most energy-demanding part of the paper manufacturing process (McGregor and Knight 1996). This review considers various ways in which investigators have sought to explain the dewatering process and to understand factors that can either increase the rate of production or reduce the consumption of energy.

To put things into perspective, one can divide paper dewatering operations into phases. The first phase involves impingement of a low-solids fibrous suspension onto one or between a pair of highly permeable fabrics, which are manufactured as continuous belts. During operation of a modern paper machine, such fabrics can travel at surface speeds up to 1900 m/min. Because the suspension impinging onto a forming fabric typically has a solids content between 0.3 and 1%, some of the water will require only gravity and inertia to flow out of the cellulosic mixture.

The next phase of the dewatering process often involves a subtle disturbance of the developing web of paper, using devices such as hydrofoils. A hydrofoil is placed on the side of a fabric opposite from where the paper is being formed, and it is designed to apply a very short-term vacuum impulse. In addition to doctoring some water from the back of the fabric, hydrofoils tend to jostle the wet web, freeing up drainage channels, and also tending to make the paper somewhat more uniform within the plane of the sheet.

A third phase of the dewatering process involves systematic application of vacuum, usually by means of vacuum flat-boxes and a perforated roll (the "couch" roll), over which the fabric travels. After passing over the couch roll, the paper web solids content is usually in the range 18-25%. Then it passes through a series of press nips, where water is forced from the sheet into the void spaces of continuous felts. After pressing, the paper web solids content usually is in the range of about 40-55%. The final operation in removing water from paper usually occurs as the sheet travels in serpentine fashion over a series of steam-heated rolls. The finished paper should have a moisture content of about 4-8%, roughly corresponding to the equilibrium moisture content of the paper under the humidity conditions at which it will be used.

According to McGregor and Knight (1996) the cost to remove one unit of moisture in the forming, pressing, and drying sections of a paper machine is related by the ratios 1:5:220. It is often possible to save energy by slowing down a paper machine, thus increasing the effectiveness of dewatering in the forming and pressing operations (Mansfield 1986). Because of the high capital costs of papermaking equipment, as well as the energy costs associated with papermaking, papermakers are motivated to find ways to produce more tons of product at a constant input of time and energy.

As noted in recent reviews, a variety of test methods have been developed to predict how rapidly water will be released during the production of paper (Kerekes and Harvey 1980; Roschy et al. 2002; Hubbe 2003). Briefly stated, these methods involve various standard conditions of filtration (Kerekes and Harvey 1980; Pires et al. 1989; Anon. 1994a), sometimes with automatic recording of the filtrate mass versus time (Sampson 1997; Bley and Falkenberg 2001), sometimes with application of vacuum (Gess 1984; Pires et al. 1989, Wang and Hubbe 2001; Roschy et al. 2002), or with pressure pulsations intended to simulate the environment of a modern paper machine (Persson and Österberg 1969; Britt et al. 1986; Lin and Schuster 1992; Räisänen et al. 1995; Sutman 2000). Some recent progress has employed computerized addition of papermaking chemicals, increasing the precision with which it is possible to evaluate different chemical strategies to promote more rapid release of water (Bley and Falkenberg 2001; Roschy et al. 2002). Even the traditional Canadian Standard Freeness test (Anon. 1994a) recently has been automated and improved in order to extract additional information that might be correlated to on-machine dewatering performance (Corscadden 2005).

Further progress has been achieved by measuring the water-retaining ability and particle size of cellulosic fines in a suspension; this approach was found to give a high correlation with the dewatering characteristics of combined furnish from which the fines were obtained (Kang and Paulapuro 2006). Because the fines fraction of papermaking furnish appears to play such a predominant role relative to dewatering rates, it should be emphasized that a wide variety of very small solid materials are apt to be present in papermaking stock. Cellulosic fines may consist of ray parenchyma cells (primary fines) or of fibril fragments removed from cell walls during refining (secondary fines). Mineral particles used as "fillers" in paper products are also counted as "fines" by many authors. Colloidal matter, including emulsion droplets, polyelectrolytes, and polyelectrolyte complexes also can be considered as fines, depending on the scope of an investigation. When considering the mechanisms to be described in the following sections, it is quite likely that different types of fines behave differently.

PACKED BED CONCEPTS

Specific Surface Area

Kozeny (1927) showed that the resistance to flow through packed beds of granular materials could be explained in terms of the size and number of pores. His ideas were extended by Carman (1938,1939), who verified the equation and introduced such concepts as hydrodynamic radius, specific surface area, and the effects of tortuosity. A commonly cited form of the Kozeny-Carman equation is given in Eq. (1),

$$k = (\gamma/\mu)\,(2/C_{\text{K-C}})\,(1/S_o^2)\,[\,e^3/(1+e)] \qquad (1)$$

where k is the permeability (length/time), γ is the unit mass of the fluid, μ is the fluid's dynamic viscosity, $C_{\text{K-C}}$ is the Kozeny-Carman coefficient (usually taken to be about 5), S_o is the specific surface area per unit displacement volume of particulate material, and e is the fractional void volume (Carrier 2002; Chapuis and Aubertin 2003). The permeability coefficient is defined in reference to d'Arcy's law,

$$\mathrm{d}V / \mathrm{d}t = k\,A\,\Delta P_f / (\mu L) \qquad (2)$$

where V is the filtrate volume at time t, A is the cross-sectional area available for flow (disregarding the presence of a solid phase), ΔP_f is the pressure drop across the permeable material, μ is the viscosity, and L is the linear length of the column through which the fluid passed through the permeable material. In cases where all of the other parameters can be determined, equations (1) and (2) sometimes are employed to estimate the specific surface area of material in a packed bed (Sullivan and Hertel 1942).

Ingmanson (1952, 1953) showed that the same concepts could be applied to compressible materials, such as cellulose. The situation considered was constant pressure dewatering through a fiber pad of uniform composition. The following equation was proposed to represent the average specific resistance, defined on a mass basis,

$$R_w = k\,S_w^2\,\Delta P_f / \{\, \int_0^p [(1-ac)^3 / c]\,\mathrm{d}p \,\} \qquad (3)$$

where S_w is the specific surface area of the fibers, a is the effective specific volume of the fibers, c is the mass of fibers in a uniform bed, and p is the compacting pressure.

Over the years, various researchers have built upon the work of Kozeny, Carman, and Ingmanson, verifying and fine-tuning the theory (Whitney et al. 1955; Tiller and Cooper 1960; Meyer 1962; Nelson 1964; Tiller and Shirato 1964; Han 1969; Kyan et al. 1970; Binotto and Nicholls 1979; Jackson and James 1986; Jonsson and Jonsson 1992a,b; Nordén and Kauppinen 1994; Mantar et al. 1995; Kumar et al. 1996; Ramarao and Kumar 1996). Whitney et al. (1955) and Jackson and James (1986) compared particulate materials having a wide range of shapes; they found that all of the results tended to fall on the same line of flow resistance as a function of the square of the characteristic radius and the volumetric content of solid matter. Such results provide strong support for the general concept. Chan et al. (1996) showed that the Kozeny-Carman equations agreed well with experimental results involving mixtures of differently shaped particles, all having roughly the same specific surface area.

The Kozeny-Carman concept also can be adapted to specific situations. For instance, Han (1969) introduced concepts of viscoelastic creep, resulting in progressive densification of fiber mats exposed to constant pressure. Binotto and Nicholls (1979) showed that Kozeny-Carman concepts can be applied with good agreement to different fractions of classified pulp suspensions differing in fiber length and wall thickness. Ramarao and coworkers (Kumar et al. 1996; Ramarao and Kumar 1996) provided an analysis of gravity-assisted dewatering, making it possible to obtain specific filtration resistance data from conventional freeness test equipment. Their model predicts that the density of the fiber pad, especially the part near to the filter screen, will go through a maximum when a fiber suspension is dewatered by gravity. Zhu et al. (1995) showed that related concepts originally developed to predict flow through textile materials also can be applied with good accuracy in the case of flow through papermaking fiber mats.

Effects of Fine, High-Surface-Area Suspended Matter

One of the hoped-for benefits of using calculations based on the Kozeny-Carman approach has been to account for effects of fine suspended matter having a relatively high surface area per unit mass, or "specific surface area." Consistent with theory, it has been found that fine mater having the smallest size and highest specific surface area tends to have the greatest adverse effect on dewatering (Przybysz and Szwarcsztajn 1973; Patel et al 1994; Liu et al. 2001). Fibrillar material, mainly composed of delaminated cell wall material, tends to cause greater reductions in dewatering rates, compared to fines having rounded or brick-like shapes, as in the case of parenchyma cells from the wood (Brecht and Klemm 1953; Steenberg et al. 1960; Waterhouse and Omori 1993; Krogerus et al. 2002; Hubbe 2002). Because fine fibrils tend to have a higher surface area per unit mass than blocky or rounded particles, such findings are consistent with the idea that specific surface area has a dominant effect on permeability.

The main effects predicted in the Kozeny-Carman equation are illustrated pictorially in Fig. 1. Consistent with the work of Marton (1980), it will be assumed that the fine matter has a much higher surface area per unit mass, compared to typical fibers in the suspension. As illustrated at right in the figure, a greater frictional resistance is expected when fluid flows through the bed of fines. Although Fig. 1 appears to imply a uniform packing of solid matter, we already have seen that not all users of the Kozeny-Carman equation have made such an assumption (e.g. Ingmanson 1952, 1953).

To apply the Kozeny-Carman equation to suspensions containing odd-shaped finely-divided matter, information about surface area is required. However, surface area within fiber lumens, within the cell wall, and within adsorbed macromolecular material at solid surfaces is not expected to affect the release of water during a conventional gravity-based or pressure-based dewatering experiment. Hence, researchers have sought various ways to assess the "hydrodynamic specific surface area" of suspended matter.

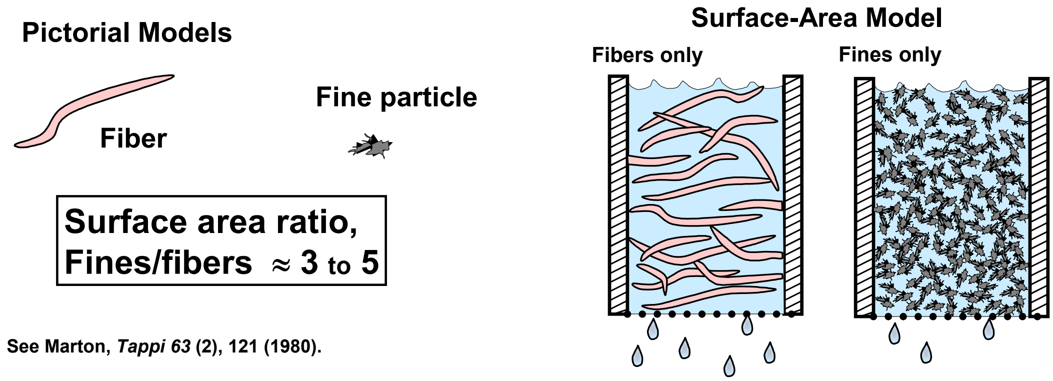

Figure 1. Left: Cartoon representations of typical fiber and typical fiber fine particle in a papermaking pulp suspension. Right: Illustration showing more rapid dewatering through a bed of coarse fibers, in comparison with fine matter, assuming uniform packing density.

Mason (1950) described how the effective hydrodynamic surface area can be estimated by either (a) determining the amount of silver needed to coat the accessible surface of suspended matter, (b) determining the efficiency of light scattering, which often is approximately related to surface area, or (c) by determining the specific resistance to filtration. In fact, Robertson and Mason (1949) were among the first to apply the concepts of Kozeny and Carman to papermaking applications. Marton and Robie (1969), as well as Wood et al. (1991) showed that related information can be obtained very conveniently by evaluating the rate at which fine particles settle out of an unstirred aqueous suspension. Wood and Karnis (1996) extended one of Mason's ideas, showing that turbidity test results, which are related to light scattering, can be used to estimate the hydrodynamic specific surface area of fiber fines. Kang and Paulapuro (2006) described use of a dynamic, centrifugal method to rapidly evaluate the rate of fine-particle sedimentation, and they also demonstrated how one can measure the viscosity of fractionated suspensions of fine matter as a means of estimating the degree to which such matter has become swollen with water.

Effects of Enzymes on Surface Area

An elegant way to demonstrate the effect of specific surface area on dewatering resistance of cellulosic material is to use enzymes. Cellulase treatments can be optimized to systematically clean up or "polish" the surfaces of fibers and fiber fines, removing fibrillar material that may be projecting outwards from such surfaces. Such a mechanism can explain why cellulase treatment after refining of kraft fibers can provide a substantial increase in drainage rates (Jackson et al. 1996; Eriksson et al. 1997a,b; Gruber and Gelbrich 1997; Seo et al. 2000; Gong et al. 2003; Gong and Bi 2005).

Effects of Wet Fiber Stiffness

Because the stiffness of fibers, when wet, can affect packing density, one would expect this parameter to affect rates of dewatering. Kayan et al. (1970) incorporated fiber bending into their model to predict filtration resistance. Lindsay and Brady (1993b) found that fibers that had been dried tended to promote more rapid dewatering, consistent with the expected somewhat irreversible effects of drying (Stone and Scallan 1966;

Klungness and Caulfield 1982; Lindström and Carlsson 1982; Nazhad and Paszner 1994; Weise et al. 1996; Maloney et al. 1998; Zhang et al. 2004). Britt (1981) also found that rapid drainage is favored by the presence of relatively stiff fibers. Paavilainen (1993) was able to quantify such concepts, using a new technique for measurements of wet-fiber flexibility.

Mixtures of Particles of Different Size

Higher packing densities can be expected in the case of suspensions that have wider distributions of particle size (Dodds 1980; Ethier 1991; Andrade et al. 1992). In effect, smaller particles can fill in spaces that would necessarily occur within suspensions consisting only of larger particles. Consistent with this effect, resistance to dewatering has been found to be larger, in the case of mixtures, than could be explained in terms of a linear combination of results from dewatering tests with uniform suspensions (Abe et al. 1979; MacDonald et al. 1991).

Deviations from Kozeny-Carman Predictions

Studies showing significant deviations from predictions based on the Kozeny-Carman concept provide evidence that other mechanisms may play significant roles in controlling rates of water release from cellulosic material. For example, Hawes and Doshi (1986) found that the origin of fiber fines, including whether or not they had been recycled, played a large role relative to dewatering rates, to a much greater extent than could be explained by differences in surface area. They proposed that the observed differences were due to differences in flexibility and conformability among the different kinds of fiber fines. As noted by Ingmanson and Andrews (1959) the classical concepts of Kozeny and Carman, even when modified to account for compressibility effects, cannot be expected to adequately deal with effects of "debris" that can contaminate an otherwise uniform porous mat.

One reasonable approach, to account for deviations from classical Kozeny-Carman concepts, would involve known differences in composition of fiber mats, as a function of distance in the direction of flow. Heath and Hofreiter (1978) provided an excellent demonstration of how simple filtration of a fiber suspension, using conventional handsheet forming equipment, can give rise to Z-directional differences in the proportions of fine materials. Under conditions of very slow, one-directional dewatering, as in the case of a Fourdrinier paper machine making a very heavy-weight product, it is possible to detect effects of more rapid gravity sedimentation of the larger fibers, leaving a higher proportion of fiber fines in the upper part of the sheet (Unbehend et al. 1989). Ramarao et al. (1994) showed that the proportion of fine matter in different layers of a mat formed by filtration can be predicted by the relative ages of different layers, during the forming process. Results were consistent with concepts proposed earlier by Parker (1972), noting that layers of fibers closer to a forming fabric have a higher probability of capturing mobilized fine matter. However, much more uniform composition in the Z direction can be achieved if the suspension is treated with a retention aid, which apparently binds fine matter to the surfaces of fibers (Tanaka et al. 1982; Ramarao et al. 1994). Mantar et al. (1995) found that dewatering results can be strongly affected by the initial solids content of fibrous suspensions. They proposed that the effects were due to

(a) increasing association between fine matter and fibers with increasing consistency, and (b) increasing tendency for fibers to entangle, forming flocs, with increasing consistency beyond a certain point (see Hubbe 2007). The distribution of fine matter in machine-made paper also is affected by the washing action of dewatering devices, such as hydrofoils and dewatering blades (Parker 1972; Zeilinger and Klein 1995).

THE CHOKE-POINT HYPOTHESIS

Fines and Dewatering

To understand the mechanisms grouped under the heading "Choke Point Hypothesis," one needs to consider the behavior of unattached fine matter in a fiber suspension, and what can happen to such fines as water is being removed. Excellent articles have been written regarding the characteristics of cellulosic materials in fiber suspensions that are small enough, individually, to pass through a conventional forming fabric of a paper machine (Brecht and Klemm 1953; Steenberg et al. 1960; Kibblewhite 1975; Htun and de Ruvo 1978; Marton 1980; Lindholm 1983; Allen 1985; Scott 1986; Gruber et al. 1997; Moss and Retulainen 1998; Luukko and Paulapuro 1999; Blechschmidt et al. 2000; Pruden 2005). Some commonly noted features of the fiber fines fraction, in addition to their small size, include a relatively high ratio of surface area to mass and a tendency to increase the resistance to dewatering. The fines fraction of a papermaking furnish usually is determined by fractionation with a standard screen (Allen 1985; Anon. 1994, 1995; Luukko and Paulapuro 1999; Pruden 2005). In terms of size, one can make an argument that small, entrained air bubbles, which likewise can increase drainage resistance (Brecht and Kirchner 1959; Gertjejansen and Hossfeld 1967; Karras and Springer 1989; Rauch and Sangl 2000; Helle and Paulapuro 2004; Martorana and Kleemann 2006), ought to be considered as part of the fines component of a papermaking furnish.

The choke-point hypothesis is illustrated in Fig. 2. Several writers have proposed that unattached fiber fines, which can move freely through the paper web during the

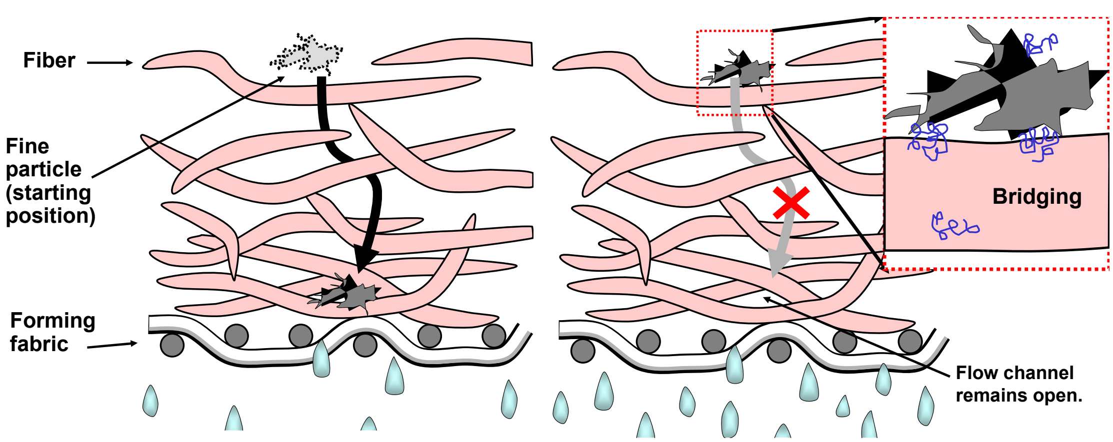

Fig. 2. Left: Schematic illustration of "choke-point" mechanism in which unattached fine particles move through drainage channels to vulnerable points at which they block the flow; Right: Proposed effect of bridging polyelectrolytes on defeating choke-point mechanism by keeping fiber fines attached to fiber surfaces.

process of dewatering, have a high likelihood of blocking channels through which the water is able to flow (Britt et al. 1986; Patel and Trivedi 1994; Kumar et al. 1996; Räisänen 1996; Wildfong et al. 2000,2003; Paradis et al. 2002; Hubbe 2002). This can be thought of as a manifestation of Murphy's law, since the movement of water through the wet web is expected to transport the fine particles until they get stuck at "choke points," *i.e.* locations in the mat that happen to be particularly unfortunate with respect to dewatering efficiency. A version of the choke-point hypothesis was enunciated as early as 1969, when Han (1969) proposed that particulate matter in the water could accumulate in a fiber mat, slowing the dewatering rate. A detailed microcopic study by de Silveira et al. (1996) revealed that fines can play a wide variety of roles in a paper sheet, some of which appear to be consistent with the mechanisms just described.

Support for the Choke-Point Mechanism: Fines Level and Basis Weight

If one begins by assuming that dewatering rates are predominantly controlled by the movement of fines to points where they tend to occlude dewatering channels, then it can be argued that the effect of fines on drainage ought to be nonlinear in character. For sake of discussion, let's envision a very simple mat of fibers in which there happen to be 100 identifiable passages for the flow of water. The first fine particle is drawn by the flow of departing filtrate into a position where it almost completely seals off flow through one of these channels, changing the overall filtration resistance by about 1%. The 50^{th} of the fines blocks the 50^{th} passage, changing the filtration resistance by about 2%. And the 99^{th} fine particle seals off the next-to-last channel, changing the overall filtration resistance by a factor of two! Although this simple arithmetic is not meant to represent a realistic description of pores in a wet-web of paper, nor the efficiency with which a fiber fine would be likely to close off a passage through a wet web, the mechanism implies that resistance to dewatering ought to increase out of proportion to the content of fines, especially when the level of unattached fine begins to approach some critical level. Data generally agreeing with the expectations just cited have been reported in several studies (Molina et al. 1984; Springer and Pires 1988; Hubbe 2002).

A related qualitative analysis can be applied to the subject of basis weight. As noted earlier in this article, fine particles have the highest probability of ending up in a layer of the paper that becomes relatively dense early in the dewatering process. At the limit of a pure filtration mechanism of dewatering (see later discussion), that layer is expected to be near to the filter screen. If the basis weight of the sheet were to be doubled, then the flow of fines-containing water that passes through that layer also will be approximately doubled. As discussed already in the preceding paragraph, each successive fine particle approaching a given layer within the mat of fibers is expected to have a progressively greater adverse impact on dewatering, so the net result is that one expects dewatering resistance to increase out of proportion with increases in basis weight. Again, experimental data from simple filtration analyses tends to support the choke point mechanism in this regard (Gess 1991; Paradis et al. 2002; Wildfong et al. 2000a,b,2003). Though the choke-point model may not be the only way to explain an increase in dewatering resistance out of proportion to basis weight (see, for instance, the "sealing" mechanism, as described later), it is worth noting that Gess (1991) observed a large, nonlinear increase in dewatering resistance with basis weight only in a case where the level of fiber fines had been artificially increased, compared to a default condition.

Mobility of Fines

Further evidence of the action of a choke-point mechanism can be obtained by controlling whether or not fine matter is free to move, relative to its initial position vis-à-vis fibers. Issues related to whether or not fiber fines and other solids within a sheet of paper are free to move, relative to a surrounding network of fibers, have been described by Parker (1972). Britt (1981) concluded, based on experiments with controlled agitation of fiber suspensions, that a majority of fiber fines would remain unattached to fibers under typical papermaking conditions. Van de Ven (1984) concluded, however, that it is relatively unlikely for very small particles to become deposited onto fibers during sheet formation, due to hydrodynamic effects. In layman's terms, the water surrounding a fiber tends to act like a lubricant, preventing close approach of small particles as they are carried past the fiber in streamlines of flow. It follows, logically, that most of the collisions, resulting in sticking of fine matter to fiber surfaces must occur earlier in the process. Another view is that electrostatic attraction forces may be able to overcome hydrodynamic forces and bring about "sticking collisions" in such cases.

The concept that fines sometimes can move freely within a paper web during dewatering is supported by studies related to a "healing" mechanism, which appears to be responsible for moderate improvements in formation uniformity (Norman et al. 1995; Sampson 1997). The idea is based on the fact that the initial fibers or fiber flocs impinging onto a forming fabric will have a nonuniform distribution. However, flow toward the forming fabric will become suppressed in those areas already covered. In this way, later-arriving fibers and fines, initially in the upper portion of a jet of slurry landing on a Fourdrinier fabric, will tend to be steered away from high-basis-weight locations and towards voids or thinner parts of the wet web. Further evidence of the relative movement of fines in the thickness direction of paper, during its formation, is shown by non-uniform distributions of fine matter, especially in the case of paper made on Fourdrinier machines, where drainage occurs in one direction (Parker 1972; Tanaka et al. 1982).

At low to moderate levels of hydrodynamic shear the simplest way to prevent fine matter from migrating through the mat of fibers is to employ a very-high-mass acrylamide copolymer, an additive that papermakers refer to as a retention aid (Horn and Linhart 1991; Doiron 1998). Many studies have reported positive effects of retention aid addition on dewatering rates (Britt and Unbehend 1980; Lindholm 1980; Wegner 1987; Karras and Springer 1989). Such results might be explained by noting that the minimum shear stress needed to detach a particle from a fiber surface exposed to flow is a strong inverse function of particle size (Hubbe 1985). The shear stress level that is just sufficient to detach a pair of fibers from each other, overcoming any polymer bridging resulting from the retention aid use, will not ordinarily be sufficient to cause detachment of a smaller particle (Britt 1981; Hubbe 1984; Hubbe and Wang 2002; Huber et al. 2004; Rojas and Hubbe 2004). Thus it is to be expected that a significant proportion of the fines fraction, following treatment of the system with an effective retention aid, will be prevented from participating in a choke-point mechanism. Retention aids can be expected to be especially effective in binding the smallest categories of fines to fiber surfaces, and such fines have been implicated in the most severe effects on dewatering (Liu et al. 2001). Small, unattached fines that are compact in character, e.g. filler particles, may have a high probability of passing through the rest of the fiber mat without becoming trapped by a filtration mechanism.

In an effort to evaluate various alternative interpretations, Hubbe (2002) carried out preliminary experiments in which a cationic acrylamide-type retention aid was added alternatively (a) just to the fines fraction, (b) just to the long-fiber fraction, or (c) to the combined furnish. These three situations are illustrated in Fig. 3, which also shows an example of how addition of the flocculant chemical to a suspension of primary hardwood fines caused the fines to become agglomerated. In each case, the fibers and fines were recombined before making a test sheet. Experiments were repeated for two kinds of cellulosic fines. The first set, primary fines, was obtained by fractionating unrefined hardwood pulp. The second set, secondary fines, was obtained by extensive refining of fines-free hardwood fibers. Parallel observations by light microscopy showed that treatments of type (a) caused agglomeration of fines, decreasing their hydrodynamic surface area. In addition, all of the treatments greatly increased the efficiency of retention during the sheet-forming process.

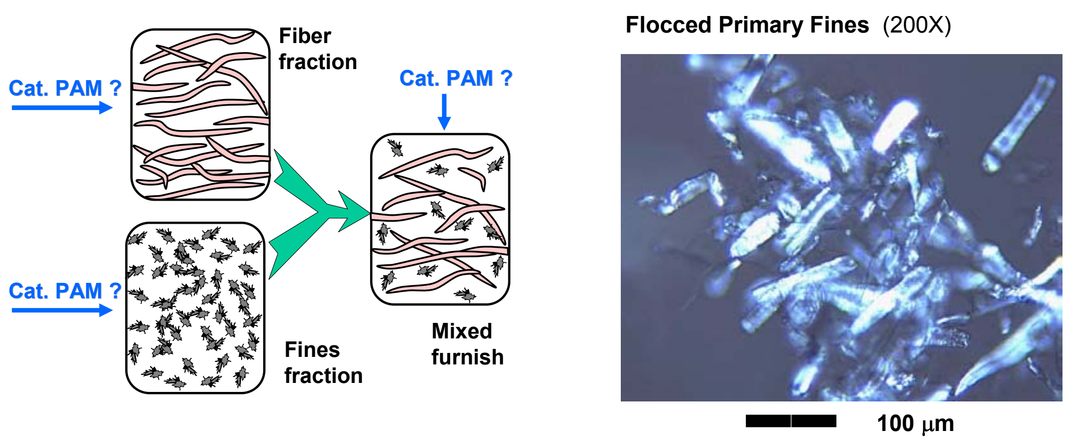

Figure 3. Summary of experimental procedure for treatment of fractionated hardwood kraft furnish either before or after recombining the fines and long fibers and noting the rate of dewatering during formation of paper. A: Treatment options. B: Agglomerated primary fines.

As shown in Fig. 4, each treatment scheme significantly increased the dewatering rates. Particularly large dewatering increases were obtained in cases (a) and (c), roughly corresponding to agglomeration of fines and attachment of fines onto long fibers. Both results are consistent with the choke-point mechanism. Related evidence can be found in studies relating the efficiency of retention to the surface charge and zeta potential of materials in fiber suspensions. Often such studies have shown maximum dewatering rates and maximum retention when aqueous conditions have been adjusted in such a way that the net electrical potential associated with the surface is near to zero (Horn and Melzer 1975; Bhardwaj et al. 2005; Hubbe et al. 2007a). Furthermore, it is well known that high-charge polyelectrolytes and multivalent ions having a charge opposite to that of fiber suspensions tend to be effective dewatering aids (Britt and Unbehend 1985; Jaycock and Swales 1994; Maunier and Ramarao 1996; Gruber et al. 1997).

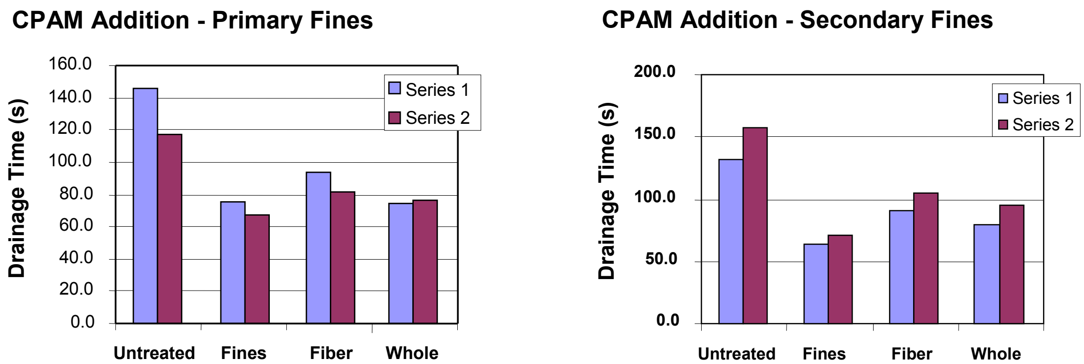

Figure 4. Experimental results for drainage time determinations with untreated bleached kraft furnish with three optional addition procedures of cationic flocculant, (a) addition to the fine fraction only; addition to the long fiber fraction only; and (c) addition to the recombined whole pulp. A: Primary hardwood fines. B: Hardwood fines resulting from refining action.

Liimatainen et al. (2006) found that scalenohdral precipitated calcium carbonate (PCC) of a type having a positive surface charge tended to promote dewatering, in contrast to other kinds of fillers that they tested. They attributed the anomalous results partly to colloidal attraction and efficient retention of the mineral onto the negatively charged surfaces of cellulosic materials. Curiously, this study was almost a mirror image of work reported by Solberg and Wågberg (2002). The latter researchers studied the retention efficiency when negatively charged ground calcium carbonate (GCC) particles were added to suspensions of positively charged fibers. In both cases attraction between surfaces of opposite charge promoted retention of filler particles on fiber surfaces.

Cases in Which Polymeric Treatments Increase Resistance to Dewatering

In some cases the addition of polyelectrolytes, e.g. carboxylmethylcellulose, has been found to increase the resistance to dewatering. Though such observations may at first appear contrary to the concepts mentioned in the previous subsection, on closer inspection some of the observations can provide further support of the choke-point mechanism. Dunham et al. (2002) observed cases in which the addition of a high-charge cationic polymer to a papermaking furnish having a high cationic demand caused a significant reduction in the rate of dewatering. It was observed that addition of the cationic polymer resulted in the formation of polyelectrolyte complexes, which remained suspended in the white water phase. This mechanism increased the particle size of colloidal material, i.e. "nano-fines," in the white water phase from 1 μm to about 20 μm, which apparently allowed the material to behave similar to fines and choke drainage channels. Interpretation of such results needs to be done with care, however, since polyelectrolyte complexes may promote more rapid dewatering in other cases.

High-mass anionic retention aid polymers often have a negative effect on dewatering (Abson et al. 1980; Gess 1993; Miyanishi and Shigeru 1997; Lee and Lindström 1989), and it can be unclear whether or not such effects are related to a choke-point mechanism. Abson et al. (1980) reported related effects in the case of an anionic retention aid, which was added to a system having aluminum sulfate present; one way to explain such results is to suppose that the alum formed a complex with the polyelectrolyte (Onabe et al. 1983). By becoming coagulated together with other such complexes, the colloidal material might become large enough to behave as small particles and block flow channels in the wet web of paper. Similar observations were reported by Polverari et al. (2001) and Pruszynski and Jakubowski (2002) in the case of high-charge cationic polymer addition to mechanical pulp furnishes, which tend to be rich in anionic colloidal material.

Related results have been reported in the case of a non-ionic retention system based on polyethyleneoxide (PEO) (Cadotte et al. 2005), except that it is not clear from the study whether or not the PEO was present in the form of complexes, or simply adsorbed onto the cellulosic surfaces. Similar effects sometimes can be observed with cationic acrylamide-type flocculants, but apparently only in cases where the system is overdosed with cationic material (Liu et al. 1986). When relatively large amounts of high-mass PEO or acrylamide copolymers are used to disperse long fibers, as in the production of wet-laid nonwoven fabrics, the same additives may be called “formation aids,” and the negative effects on dewatering rates can be very substantial (Lee and Lindström 1989).

Time Effects that Support the Choke-Point Mechanism

The beneficial effect of drainage aids often has been found to pass through a maximum, several seconds after addition of the chemical to an agitated fiber suspension, and then to gradually decay with the further passage of time (Forsberg and Bengtsson 1990; Forsberg and Ström 1994; Hubbe and Wang 2002). Such observations can be explained in terms of an initial deposition of fine solids onto fiber surfaces, followed by gradual re-entrainment into the white water phase. It makes sense that the added cationic polyelectrolytes should initially form bridge-like or patch-like connections (La Mer and Healy 1963; Gregory 1976) between the fine matter and the fibers. However, the passage of time and the influence of hydrodynamic shear can shorten the molecular chains (Sikora and Stratton 1981; Tanaka et al. 1993; Forsberg and Ström 1994) and allow the polymeric additives to lie down flat on the fiber surfaces (Swerin and Ödberg 1997), or to become buried beneath a layer of fibrillation (Hubbe 2006).

Support for a mechanism involving conformational change and/or progressive migration of cationic polymers into pore spaces below fibrils at the fiber surface is provided by a study involving parallel measurements of dewatering and zeta potential (Ström and Kunnas 1991). Greater efficiency, in terms of dewatering, was observed in the case of higher-mass cationic polymers, which appeared to stay on the outer surfaces of suspended matter for a longer time. Based on such observations it makes sense to add dewatering aids relatively late in the approach system to a paper machine forming section, maximizing the degree to which fine particles are being held onto fiber surfaces during the forming process.

Water Retention Values (WRVs)

Published evidence does not support that idea that high-charge polymeric additives have a large effect on the water that is held within the walls of cellulosic fibers.

Such a "de-swelling" action is among the possible mechanisms that might be used to explain the action of high-charge cationic dewatering aids (Auhorn 1982; Allen and Yaraskavitch 1991). Procedures involving centrifugation of damp plugs of fiber, allowing the filtrate to pass through a filter and into absorbent material, have been used for many years to estimate the amount of water that is contained within fiber cell walls (Thode et al. 1960; Jayme and Büttel 1968; Ahrens et al. 1999; Anon 1981, 2000). However, if drainage aids mainly functioned by penetrating within the cell walls of fibers, then one would expect their effectiveness to increase with decreasing molecular mass. In fact, the opposite is true (Ström and Kunnas 1991). Highly charged cationic polymers having relatively high mass were found to be much more effective at promoting dewatering, and they also had a much bigger effect in decreasing water retention values, as measured by the centrifugation. It was concluded that the WRV effects were mainly associated with water hold on the outsides of fibers, within layers of fibrillation. The most effective dewatering aids were those having capability to form large positive patches of charge, causing agglomeration of the fibrils. A related study showed that cationic polymers had relatively little effect on water retention values (Maunier and Ramarao 1996), but caused big increases in dewatering rates.

Pulse Dewatering as a Demonstration of the Choke-Point Mechanism

A key piece of evidence can segue to the next topic. Dewatering tests involving controlled levels of flow or vacuum pulsations often show greatly accelerated rates of dewatering, and much less sensitivity to the presence of fines (Britt et al. 1986; Räisänen 1996; Räisänen et al. 1996; Mitchell and Johnston 2000; Rojas and Hubbe 2004). At least part of the dewatering enhancement effect probably can be attributed to the washing of fine material from the wire-side(s) of the wet web of paper (Egelhof and Bubik 1994; Zeilinger and Klein 1995; Räisänen et al. 1995; Räisänen 1996; Hubbe et al. 2006a), thereby defeating the choke-point mechanism.

SEALING AS A MECHANISM OF DEWATERING RESISTANCE

Even in cases where fines do not move freely within a fiber suspension, there is another mechanism that can inhibit flow through the densest layers in the wet web of paper, as it is being formed. That mechanism is sometimes called "sealing." The idea is that conformable cellulosic materials are forced together, as a result of applied vacuum or wet-pressing, such that they seal off passageways by which water might have more easily escaped from the wet web (Wildfong et al. 2000). The mechanism is illustrated schematically in Fig. 5.

As in the case of a rubber plug in an old-fashioned sink, the higher the pressure, the more effective becomes the sealing action. McDonald and Amini (1998) were able to apply this type of interpretation to explain dewatering resistance on a linerboard former. Wet sheets were pressed under different pressures in order to estimate the degree to which flow would be sealed off under different conditions of vacuum application during paper formation. Pires et al. (1989) observed cases in which resistance to flow increased out of proportion to the applied pressure, consistent with sealing.

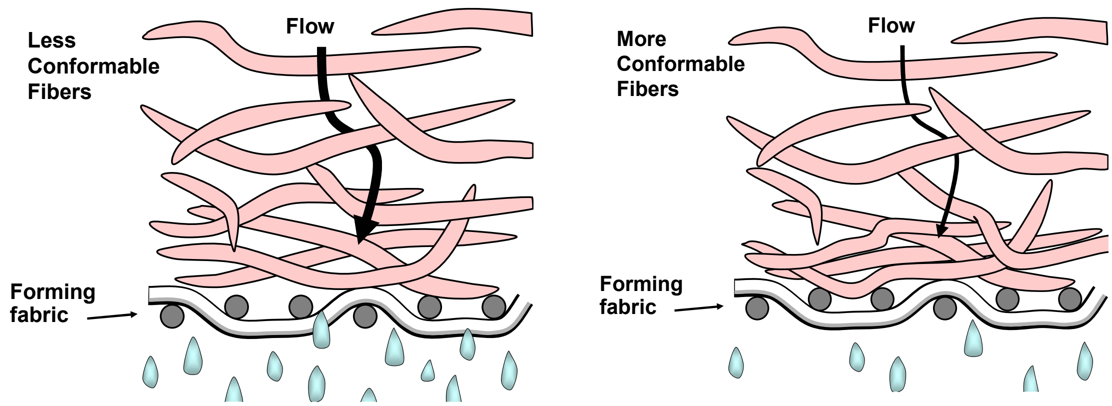

Figure 5. Schematic illustration of “sealing” mechanism in which the fibers in a paper mat are sufficiently flexible that pressure causes them to squeeze together, sealing off flow

Evidence to support a sealing mechanism of resistance to dewatering comes, first of all, from measurements of fiber flexability and conformability (Tam Doo and Kerekes 1982; Steadman and Luner 1985; Paavilainen 1993). More flexible fibers resulted in greater resistance to dewatering. Corroborating evidence comes from studies of fibers that have been recycled under laboratory conditions. An observed increase in freeness when never-dried fibers are formed into paper, dried, and then resuspended in water can be attributed to irreversible stiffening of the fibers (Paavilainen 1993; Dulemba et al. 1999; Zhang et al. 2004).

A sealing mechanism also can help explain the effectiveness of dewatering devices that produce short pulses of applied vacuum. If one assumes that sealing is the dominant mechanism limiting dewatering rates, then one would expect there to be diminishing rates of dewatering whenever vacuum is applied at a steady level (Mitchell and Johnston 2000). Indeed, the most effective dewatering, by means of vacuum flatboxes, usually requires optimization of the spacing and duration of vacuum pulses (Persson and Österberg 1969; Giles 1990; Räisänen 1996; Baldwin 1997). Lindberg (1970) observed that the application of vacuum in the form of pulses became increasingly important with increasing flexibility of the fibers, consistent with a sealing mechanism.

Many papermakers believe that sheet sealing effects mainly can be attributed to an interaction between fibers and the forming fabric. This subject has been reviewed in exquisite detail by Kufferath (1982). The idea is that, especially under conditions of rapid initial dewatering, fibers become pressed into the openings of a forming fabric, effectively rendering the fabric less porous (Giles 1990; Miller 1998). The importance of interactions between a fabric and the initial fibers impinging upon it has been demonstrated by turning a forming fabric upside-down and observing large differences in dewatering performance (Giles 1990). However, another careful study failed to find any special contribution that could be attributed to the first layer of fibers to land on the fabric (Herzig and Johnson 1999).

INTER-FIBER FRICTION AND ITS INFLUENCE ON DEWATERING

In addition to the "sealing" mechanism, as just considered, another closely related mechanism appears to play a significant role with respect to the use of dewatering agents. That is, if fibers in a papermaking furnish are able to slide past each other when they come into contact, then one can expect that they will tend to form a relatively dense mat during the forming process. If, on the other hand, they tend to stick together and not slide past each other, then one can expect a more bulky, porous mat of fibers from which water can more easily flow. In other words, the degree to which the furnish components tend to become packed together is expected to play a major role in determining the permeability of the mat that is formed (Sampson and Kropholler 1995).

One way to find out whether fibers in suspension will tend to stick to one another on contact involves rheometric measurements. If the solids content of a fiber suspension is sufficiently high, then it can be feasible to measure the yield strength of a transient network that forms among the fibers upon secession of flow. Swerin et al. (1996) showed that such yield strength values could be greatly increased by the addition of flocculating polymers. At the other extreme, Zauscher (2000) measured frictional forces between submicroscopic surfaces, using atomic force microscopy (AFM). He found that the coefficient of friction generated between pairs of cellulosic surfaces in the presence of water could be greatly reduced by the addition of carboxymethyl cellulose (CMC).

Many of the effects that polyelectrolyte additives can have on inter-fiber friction in the wet state can be understood in terms of electrostatic forces of interaction. A particularly effective way to prevent cellulosic surfaces from sliding easily past one another is to treat the system so that the surfaces are partially covered with "patches" of high-charge cationic polymer. Indeed, polyelectrolytes having suitable molecular mass and high charge that is associated with a patch-type mechanism of agglomeration (Gregory 1976; Goossens and Luner 1976; Akari et al. 1996; Pfau et al. 1999), tend to be effective dewatering aids (Gruber et al. 1996). The general principle of patch-type agglomeration was demonstrated by Das and Lomas (1973), who treated half of a batch of cellulosic fines to make them strongly cationic. When such fines were recombined with untreated fines, having negatively charged surfaces, very strong agglomeration was apparent.

As observed by Noda et al. (2005), substantial decreases in dewatering resistance can be achieved by addition of cationic surface-active agents, which are often used as debonders to reduce the dry strength characteristics of the resulting paper. Because one can expect the positively charged groups on the surfactant to become associated with the negative surfaces of the fibers, it follows that the hydrophobic tails of the molecules will be free to self-associate, especially when a pair of fibers comes into contact. Such a mechanism would be expected to result in higher frictional forces between the fibers. The same mechanism also can explain why fiber mats formed in the presence of cationic surfactants also tend to be much more bulky and porous. Unfortunately, strategies based on the mechanism just described are not suitable for the majority of paper grades, where dry strength usually needs to be relatively high.

Inter-fiber friction also can be evaluated by allowing a treated fiber suspension to settle, and then evaluating the density of the sediment formed after a selected period of time and under standardized conditions (Kline 1967; Alince and Robertson 1974; Gruber et al. 1997; Hubbe et al. 2001). Relative to the other test methods, sediment volume tests can sense effects resulting from very small and transient forces of attraction or repulsion between fibers. Treatments that tend to increase values of sediment volume also tend to increase dewatering rates under controlled conditions. The effect is illustrated in Fig. 6.

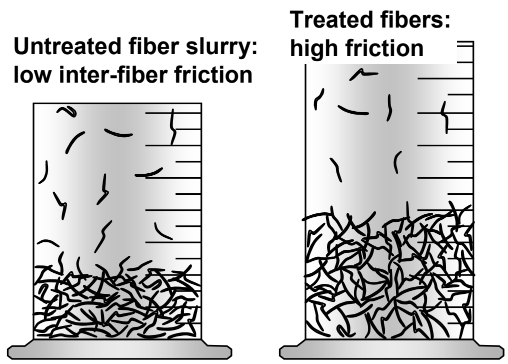

Figure 6. Illustration of sediment volume test with papermaking fibers in the absence and presence of a coagulant

As proposed by Lindström (1989), the most effective polyelectrolyte-based dewatering aid programs tend to be those that can be classed as "reversible." In other words, such systems will tend to form flocs again following application of sufficient hydrodynamic shear to completely redisperse the fibers from each other. The idea is that modern paper machine headboxes and other unit operations exert very strong forces of detachment on fiber systems, causing essentially all of the fiber-to-fiber polymer bridging contacts to be broken at least once before the sheet becomes established in the forming section. But in order for chemical systems to function most effectively as dewatering aids, they need to still have some residual agglomerating ability, even after being subjected to rather intense hydrodynamic shear. In addition to the cationic patch-type treatments already mentioned, microparticle-type drainage aid programs exhibit some reversibility in their flocculation behavior (Lindström 1989; Litchfield 1994; Swerin et al. 1997; Hedborg and Lindström 1996; Hubbe 2001, 2005).

FIBER ALIGNMENT AND FLOW RESISTANCE

If one could align wet fibers in the manner that combed wet hair becomes aligned, then it is likely that one could achieve a significant decrease in permeability through a fiber mat. Such a mechanism even may be responsible for the "sheet sealing" effects described earlier. Evidence for this kind of mechanism has been obtained in studies where dewatering occurred in the presence of controlled hydrodynamic shear (Forsberg and Bengtsson 1990; Arslan et al. 1997; Paradis et al. 2003). For instance, controlled shear could be applied by using a rotor having the shape of a shallow cone positioned close to the dewatering screen (Paradis et al. 2003).

As a counter-example, is appears that significantly more permeable wet paper mats can be created under conditions where the fiber orientation is chaotic, including a high degree of out-of-plane alignment. It is well known that such chaotic alignment can be achieved by forming paper at relatively high solids content of the suspension. Paper formed under such conditions has been shown to have a reduced resistance to dewatering (Ingmanson and Whitney 1954; Ellis 1981).

PAPER UNIFORMITY AND VACUUM RESPONSE

The remaining experimental evidence that will be considered has particular relevance to vacuum dewatering, in addition to dewatering within wet-press nips. In a classic piece of investigation Britt and Unbehend (1980) demonstrated positive effects of various dewatering aid treatments on the release of water during simple gravity-filtration of fiber suspensions. But parallel tests, carried out with application of vacuum, gave contradictory results. Rather than aiding in the dewatering, the cationic polymers, when used alone or in combination with an anionic acrylamide-type retention aid, resulted in substantially wetter fiber mats following a standardized application of vacuum.

The inconsistent results were attributed to the formation of persistent fiber flocs by the polyelectrolyte treatments. More rapid dewatering by gravity was achieved due to the ability of water to flow quickly within the large void spaces that surround fiber flocs. But once most of the water has been removed by application of vacuum, the same void spaces allow air to rush ineffectively through the wet web, failing to maintain a pressure differential across the thickness of the sheet. Confirmatory results were obtained by Scalfarotto and Tarvin (1984) and by Wegner (1987). The latter study also showed that the more highly flocculated sheets required longer application of heat in the drying operation in order to evaporate the remaining water.

Britt (1981) recommended at least moderate levels of refining of kraft fibers, in addition to vigorous agitation, in order to achieve uniform formation, as is required for an efficient response to vacuum application. Also, as observed by Britt and Unbehend (1985), the presence of a moderate level of fiber fines in the furnish can significantly improve vacuum dewatering, in comparison to a furnish from which the fines fraction has been removed. Not only do fiber fines tend to fill in void spaces within a wet web of paper, but also, as shown by Youn and Lee (2002), fines in the suspension can reduce the tendency of fibers to flocculate. All of these results are consistent with the formation of a tight, uniform wet-web that does not allow rapid leakage of air. Follow-up experiments on a pilot-scale paper machine showed that the most rapid dewatering could be obtained if, after addition of a highly effective flocculant system, including a highly charged cationic polymer, the furnish was agitated vigorously to fully disperse the fibers from each other (Britt and Unbehend 1980).

As one gets towards the upper limit of solids content that can be achieved by application of vacuum, it can be expected that a significant fraction of the water remaining within paper exists in thin films that occupy spaces between adjacent fibers and other solids (Maloney et al. 1999). Such films can help to explain why plugs of moist fiber that have been subjected to centrifugation tend to be wettest in the lower layer, where the fibers were pressed together most tightly during dewatering (Abson and Gilbert 1980). As noted by Jones (1998) one can expect vacuum dewatering, at a given pressure differential, to reach a maximum, when all of the pores larger than a critical size have been emptied. Capillary pressures, which are inversely proportional to effective pore radius, can make it impossible to empty smaller pores.

PUMPING AS A DEWATERING MECHANISM

As already noted, the washing action of hydrofoils may tend to counter-act the choke-point mechanism of resistance to dewatering. However, there is a further effect of pulsating vacuum that may play a role once the wet web reaches the vacuum dewatering section of the forming zone. Räisänen et al. (1995) proposed that the part of the wet web nearest to the forming fabric can act as a sort of pump. The way in which this happens is by the layer becoming strongly compressed, when the wet web passes over a slot in a vacuum box. As the compressed layer recovers its equilibrium thickness, it may draw water from the rest of the wet web. The mechanism is supported by the relative futility of applying an individual vacuum pulse too long at a given pressure (Baldwin 1997; Jones 1998). Such a practice might be compared to application of further pressure to a spring after it has become almost fully compressed.

WATER HELD WITHIN FIBERS

An even more difficult to remove category of water exists within the cell walls of fibers. As mentioned already, such water is commonly estimated by centrifugation of a damp plug of fibers, weighing the damp fibers, and then weighing them again after oven drying (Thode et al. 1960; Jame and Büttel 1968; Scallan and Carles 1972; Scallan and Tigerstrom 1992; Anon. 1981, 2000). The results of such tests are expressed as the water retention value (WRV), which is the ratio of water to fiber solids after centrifugation for a specific time at a specified level of acceleration (Anon. 1981, 2000). Cell-wall water content also can be evaluated by suspending a known mass of fibers in a known mass of water that contains a known concentration of high-mass dextran polymers (Scallan and Carles 1972; Scallan and Tigerstrom 1992; Maloney et al. 1999). One makes the assumption that the dextran molecules are too large to enter small pores within the cell walls of fibers and that they have no significant tendency to adsorb onto cellulose. By measuring the concentration of the sugar molecules in the bulk phase, one then back-calculates what must have been the net volume of pores that were too small to allow entrance of the polymers. Such a method even has been applied in the case of fiber fines, showing that recycled and rewetted fines tend to hold onto much less water, compared to their swollen state before their first cycle of drying (Laivins and Scallan 1996).

It appears doubtful that the swollen state of cellulosic materials can be affected to a significant extent by addition of dewatering aids, though more experimental evidence is needed. Swerin et al. (1990) reported significant decreases in water retention value following treatment of refined fiber suspensions with highly cationic polyelectrolytes of low to moderate molecular mass. However, related results obtained by Ström and Kunnas (1993) provide evidence that most of the effect of such polyelectrolytes is restricted to a dewatering effect involving fibrillated layers. The mechanism is illustrated in Fig. 6, which depicts coagulation of a fibrillated layer by cationic polyelectrolyte molecules, though it is assumed that such molecules do not readily penetrate into the nanopores of the cell wall. As was noted earlier, the greater effectiveness of higher-mass polyelectrolytes in reducing the WRVs of treated suspensions probably can be attributed to enhanced effectiveness of the charged-patch mechanism of agglomeration, as well as a decreased tendency for the polyelectrolytes to become buried within smaller pores.

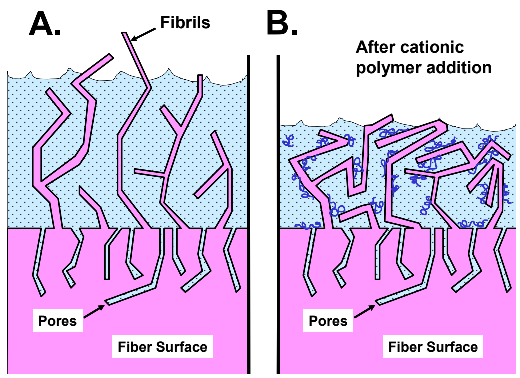

Figure 7. Illustration of how the coagulating effect of high-charge cationic additive (possibly acting by a charged patch mechanism) might decrease the amount of water held within layers of fibrils at fiber surfaces.

Some limited research has suggested that significant amounts of water can be associated with water-soluble polymers or polymer complexes held within a wet web of paper. For instance, Carlsson et al. (1977) measured significant increases in water retention with increasing levels of cationic acrylamide copolymer addition to mechanical pulp slurries. Hubbe et al. (2007b) observed increases in water retention when glass microfibers were treated with polyampholytes, which are polyelectrolytes having both negative and positive ionic groups. Further research is needed to determine whether such effects can be significant over a broad range of polyelectrolyte types and furnish conditions.

COMPRESSION RESISTANCE AND WET-PRESS DEWATERING

It can be very challenging in the laboratory to estimate the maximum practical solids levels that can be achieved by wet-pressing of paper. Tests involving application of static pressure are not expected to give realistic predictions, due to the very short periods of time during which a wet web passes through a press nip. A number of researchers have attempted to evaluate wet-press dewatering by using devices that apply a hammer-like impulse (Zotterman and Wahren 1978; Davis et al. 1983; Carlsson 1984; Springer et al. 1989). Tests of wet-press dewatering generally have failed to show significant effects that could be attributed to prior treatment of the furnish with chemical additives (Wegner 1987), though it is quite likely that the noise-to-signal ratio within the data would have obscured any such effects.

When a wet web of paper passes through a press nip, two types of forces are mainly responsible for preventing crushing of the sheet. One of these components of force results from hydrostatic pressure. Such pressure is a direct consequence of the factors that resist dewatering, i.e. frictional effects as water is squeezed through narrow passageways. But in addition to the hydrostatic component, the compressive forces also are resisted by the mechanical strength of solid components within the paper web (MacGregor 1983ab; Szikla and Paulapuro 1989). The interplay between these two classes of forces helps to explain, among other things, why paper sheets tend to become highly densified in the layers that lie nearest to a porous felt as the sheet passes through a press nip.

Very little research has been carried out to determine whether or not papermaking additives can contribute to the structural component of compression resistance in a wet web of paper. As an exception to this rule Fairchild (1992) showed that paper manufactured with a highly bulky, rosette-shaped form of precipitated calcium carbonate (PCC) filler tended to retain more water content after pressing, in comparison to paper that was made with PCC having a less bulky particle shape.

In the production of many paper grades, and in particular xerographic copy paper, file folder stock, and folding boxboard, it can be a great advantage to maintain a low apparent density in the final product. The challenge comes in trying to figure out how to press water effectively from a wet web of paper without irreversibly densifying it. One of the most promising strategies, in this regard, appears to involve the use of spring-like fibers, having the ability to recover some of their initial three-dimensional character after being squashed flat in a press nip. In this regard, mechanical pulp fibers usually can be described as being "tougher" in comparison to kraft fibers. For instance, it has been proposed to use chemithermomechanical pulp (CTMP) fibers in order to compensate for increased density when paper is prepared with a very high mineral content (Moberg 1985). Another approach involves directing the jet of fiber suspension at a relatively steep angle of impingement onto the forming fabric, i.e. pressure forming. By such means it is possible to achieve a higher proportion of fibers having orientations other than in the plane of the sheet. In principle, one expects there to be a relationship between out-of-plane fiber orientation and the ease of dewatering from paper. Issues of this nature deserve greater study in the future.

PRACTICAL STRATEGIES FOR DEWATERING OF PAPER

Having discussed many different contributing mechanisms to explain the resistance to water release from paper, as it is being formed, this final section will be devoted to a summary of the main strategies that have been used to accelerate such dewatering. The goal here is to translate some of the chemical-related concepts outlined in this review to practical measures that can be implemented in a paper machine system. Items in the following list are arranged roughly in the same order as in the foregoing discussion:

Table 1. Common Strategies for Promoting Faster Dewatering

Dewatering Enhancement Strategy	Principle of Action
Minimize refining	Surface area minimization; keeping fibers stiff
Limited furnish treatment with cellulase	Reducing hydrodynamic surface area
Heat up the wet web (steam box)	Reducing viscosity of aqueous solution
Add high-charge cationic polymer or alum	Coagulation of fiber fines and fibrils.
Aim for near-zero zeta potential of solids	“ “ “ “
Use a high-mass polyelectrolyte flocculant	Attaching fiber fines so they can’t choke channels
Use once-dried fibers, without more refining	Stiffer fibers forming a bulkier, more porous mat
Agitate flocculated fiber suspension	Breaking up fiber-to-fiber attachments
Employ microparticle retention chemistry	Optimizing reversible attachments, friction
Use filler having less structure	Less resistance to sheet compression
Use filler having less surface area	Less viscous resistance to water flow in web

In summary, most of the principles outlined in this review have the potential to be implemented during industrial operations. Though the mixtures of materials and the flow environments present in a paper machine system generally are too complex to be described in scientific detail, enough is known about the underlying mechanisms to allow an efficient search for new and better means of promoting the release of water. This kind of technology will continue to hold promise for further savings in evaporative energy, as well as for increasing the rates of production on existing papermaking equipment.

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