Filling Wet Paper with the Use of a Secondary Headbox

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Pilot-scale trials on slow and fast Fourdrinier paper machines have shown that a sheet can be filled with clay and calcium carbonate by passing a concentrated filler suspension through a wet sheet. The suspension was supplied from a secondary headbox located at the dryline. The trials showed that no damage to the sheet occurs when the filler suspension is applied to the wet sheet. At low filler concentrations, an uneven distribution of filler in the sheet was observed in the *z* direction, but at high filler levels, the unevenness in filler distribution decreased. The strength of the paper decreased with increasing filler concentration, as is the case in conventionally filled paper. Aside from fillers, other chemicals can be retained by this process as well. Polyethylene imine (PEI) showed an increase in the dry strength of paper on the slow Fourdrinier machine, but not on the fast one. The main advantage of this method is that the filling process can be completely separated from the wet-end chemistry.

Introduction

Fillers are added to paper to improve various paper properties and to reduce cost. They are traditionally added to the papermaking furnish prior to the formation of the sheet, and additional additives, such as retention aids, must be used to efficiently incorporate fillers into a sheet. As a consequence, the use of fillers leads to more complex wet-end chemistry, and their limited retention causes an accumulation of fillers and other additives in the whitewater. Additional problems are that the efficiency of retention aids is often reduced by dissolved and colloidal substances present in the whitewater. Fillers in process water can also contribute to the stabilization of unwanted foams.

For all of these reasons, it would be desirable if the filling of paper could be achieved in a unit operation that is completely separated from the wet-end processing. In this article, we report on a new way to achieve this separation, namely, by filling paper after the sheet is formed and while it is still wet before it enters the press section. Similar concepts in the wet-end processing of the paper machine involve the manufacturing of laminated cardboards, the spraying of starch, and the curtain coating. A secondary headbox is used for laminated cardboards to apply a fiber suspension onto a preformed base sheet. The base sheet usually has inferior optical properties, and the aim of the secondary layer is to improve the properties while reducing the production costs by using a minimum amount of expensive high-quality fibers. The curtain-coating technology uses a free-falling flat jet called a curtain as a single- or multiple-layer coating of photographic films and papers, magnetic recording tapes, etc.[1−3] Curtain coating is not used for pigment coating because of paper machine runnability problems under high-speed conditions.[4] The starch-spraying process can be used either in conjunction with a size press or as an alternative to conventional sizing. During the treatment, the starch granules are applied to paper in the form of a spray.[5,6] The main advantage is high starch retention (excess of 90%). Both techniques, curtain coating and spraying, have many similarities with the proposed novel method to paper loading, as the amount of additives and the penetration depth can be varied.

The filling of a paper sheet using a secondary headbox is based on replacing the water in the wet sheet with a suspension of fillers. The advantage is that this process is insensitive to the quality of the water in the sheet and that the filler that passes through the sheet can be collected and fed back to the filler suspension. This leads to two completely separate recirculation loops, one for each fibers and pigment. The actual filling of the wet paper can be done with or without the use of retention aids. The use of surface-treated fillers that have favorable fiber−filler interactions is also straightforward. Because most of the water is already removed when the sheet is formed, little dissolved material is left to interact with the polymers used for the surface treatment. Aside from filling the sheet with pigments, this process can be used to apply any other additives, such as strength agents, sizing agents, yellowing inhibitors, etc. The method of filling wet paper has already been successfully studied under stationary conditions (with a nonmoving sheet).[7] A disadvantage of displacement filling is that the sheet is wetter when entering the press section of the paper machine, which might necessitate increased nip loads. Alternatively, an additional vacuum section could be installed before the press section.

Filling Wet Paper Using a Secondary Headbox

The principle of filling wet paper is shown schematically in Figure 1. In essence, it consists of the displacement of water in the sheet by a suspension containing fillers. A concentrated suspension of fillers flows out of the slice of a secondary headbox with a velocity of v_s, whereas the paper moves through the paper machine with the velocity v_p. If the differential velocity, $v_p - v_s$, is too large, the possibility exists that the impingement of the suspension on top of the sheet will rupture the

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10.1021/ie034203i CCC: $27.50
Published on Web 03/26/2004

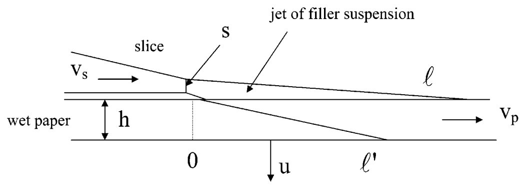

Figure 1. Schematic drawing of water replacement in a wet sheet with a filler suspension.

sheet. However, this was not found to be the case, even for $v_p = 2v_s$. If suction is applied from below, water from the sheet will be removed and replaced by a filler suspension. Eventually, the filler suspension will be sucked through the sheet as well.

Filler will reach the other side of the sheet when it has traveled a distance l' (see Figure 1), which is approximately given by

$$l' = \frac{hv_p}{u} \tag{1}$$

where h is the thickness of the sheet and u is the average drainage velocity in the filling section. Because of continuity, the velocity u is also related to the height, s, of the slice opening of the secondary headbox

$$s = \frac{lu}{v_s} \tag{2}$$

where l is the location of the dryline of the filler suspension. Combining eqs 1 and 2 yields

$$\frac{l'}{l} = \frac{hv_p}{sv_s} \tag{3}$$

For displacement filling to occur, the amount of liquid entering the sheet from above, ul, must be larger than or equal to the amount leaving the sheet at the bottom, ul'; hence, $l > l'$, which implies $v_s > hv_p/s$. Thus, for low application velocities, such as those used in spraying and curtain coating, the applied liquid does not penetrate the sheet fully, but is confined to the surface layer. In this respect ,displacement filling is different from other wet-sheet applications. When $v_s = v_p$, s must be larger than h, whereas when $v_s = 0.5\ v_p$, s must be larger than $2h$. These two conditions apply to the two pilot machines discussed below. Given that h is typically about 1 mm at the (secondary) dryline, a slice opening of 3 mm was chosen for all trials. Equations 1–3 can be used to estimate the location of the dryline for given drainage conditions.

Obviously, the description of displacement filling given here is highly approximate. First, the drainage velocity is not constant, but varies along the machine. Also, channeling can occur,[8] which can result in the bypassing of certain water regions in the sheet. Nevertheless the description provides us with approximate values of required slice openings of the secondary headbox and the corresponding dryline locations.

We decided to place the secondary headbox at the dryline. Locating it before this position makes no sense, because one would also have to displace the water on top of the sheet. Placing it further down the drainage section could be considered, but higher solid contents lead to a higher resistance to flow through the sheet. Also air entrainment in the sheet would result in an uneven distribution of filler.

Materials

Slow Fourdrinier Machine. Unbeaten, bleached softwood kraft pulp was used for the formation of a base sheet. The consistency of the pulp in the primary headbox was 1%.

Alkaline kaolin clay was used as a pigment. This clay was comparable in size (equivalent spherical diameter of 200 nm) and properties to the clay used in preliminary experiments on a stationary sheet.[7] The clay was introduced to the formed sheet of paper either untreated or treated with polyethylene imine (PEI).

Polyethylene imine (PEI) under the commercial name of Polymin P was utilized for the clay treatment. Given that PEI is cationic, the role of PEI was to render the clay positive and, therefore, to enhance the mutual electrostatic attraction between the pigment and the negatively charged fibers. The PEI was also passed through the formed wet sheet to study the possibility of applying polymers through the secondary headbox and also to determine the effect of PEI on strength properties.

Fast Fourdrinier Machine. Never-dried, unbleached softwood kraft pulp was beaten to 550 mL CSF (Canadian standard freeness) to achieve optimum runnability of the pilot machine (as determined from prior experience). The pulp consistency in the primary headbox was 1%.

The precipitated calcium carbonate (PCC) Albacar HO was used as a filler. The filler has a diameter about 1 μm and a surface area of 12 m^2/g. The surface charge of PCC suspended in deionized water is slightly positive; however, it can become negatively charged in contaminated process waters. In addition to the water quality, the PCC concentration also affects the surface charge.[9] The water used in all of the experiments was clean (tap-water quality) and was never recirculated.

Anionic acrylic acid based stabilizer was used to treat the PCC to provide PCC with a strong negative charge. In this case, the PCC negative charge serves to maximize the electrostatic repulsion between the pigment and negatively charged fibers.

Cationic starch CATO 237 was used to treat the PCC pigment. The role of the cationic starch was similar to that of PEI, i.e., to render the pigment positively charged. The cationic starch was also passed through the already-formed wet sheet.

Polyethylene imine (PEI) under the commercial name of Polymin P was utilized for the PCC treatment and was also passed through the formed wet sheet.

Pilot Paper Machines

Pilot trials were performed on two experimental Fourdrinier machines: a slow machine (CSSP in Trois-Rivières, Quebec, Canada), running at $v_p = 0.67$ m/s, and a fast machine (GL&V, Watertown, NY), running at $v_p = 10$ m/s. On both machines, a secondary headbox was used and was located at the dryline with a slice opening of $s = 3$ mm. The widths of both machines were 68 cm, and the basis weights were in the range of 85–110 g/m^2. On the slow machine, $v_s = v_p$, whereas on the fast machine, $v_s = 0.5v_p$.

A schematic diagram of the setup for filling wet paper is shown in Figure 2. A filler suspension (clay for the

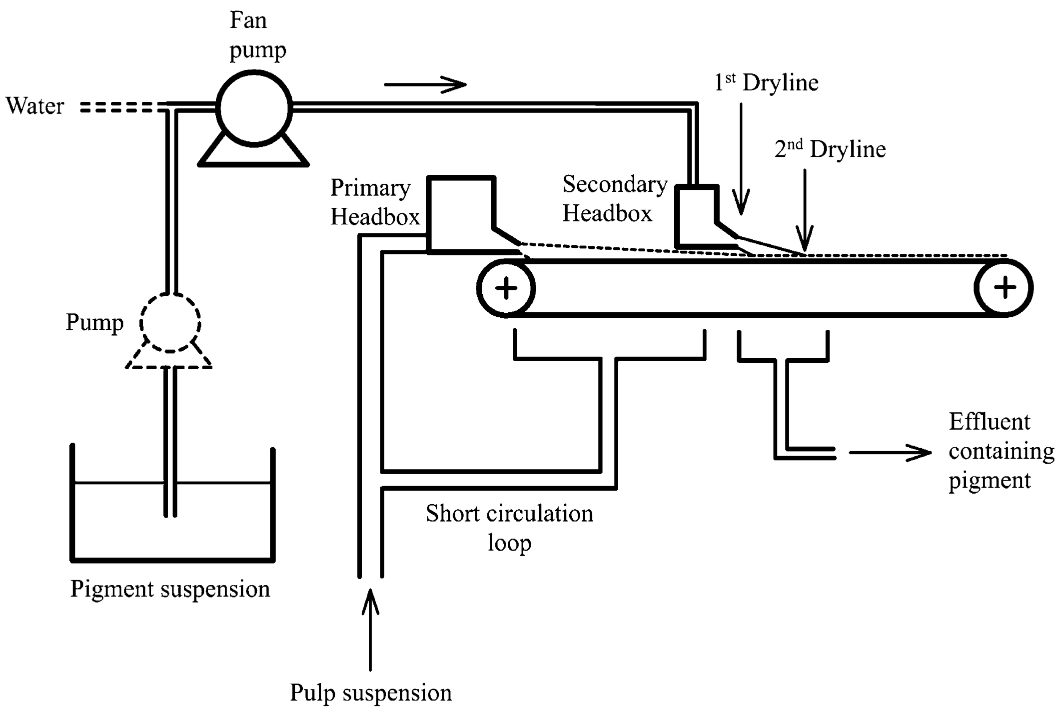

Figure 2. Schematic drawing of filling wet paper on a Fourdrinier machine equipped with a secondary headbox. On the slow machine, the filler suspension was pumped directly to the headbox using the fan pump only. On the fast machine, the filler suspension was pumped (dashed pump) into a waterline (dashed) that fed the secondary headbox.

slow machine, PCC for the fast machine) was pumped from the mixing tank to the secondary headbox. On the slow machine, a constant flow rate was achieved by means of an overflow, thus creating a constant pressure to drive the flow. On the fast machine, a secondary fan pump with a flow rate of 3 L/s pumped water to the secondary headbox, and the filler suspension was injected in this flow line with a velocity of 0.75 L/s. On the slow machine, all of the paper was dried on the machine, whereas on the fast machine, wet paper after the press was collected for periods of a few seconds and was dried off-line. Photographs of the secondary headbox operating at both machines are shown in Figure 3.

For the slow machine, eq 3 predicts that the distance between the slice and the dryline, l, is about 20 cm, assuming a drainage velocity of 1 cm/s, which is typical.[10] On the fast machine, assuming that the drainage is twice as fast, we expect the dryline to be at $l \approx 75$ cm. These values are close to the observed values, indicating that estimated drainage velocities are realistic (cf. Figure 3).

Trials were first performed on the slow Fourdrinier, to establish the validity of the filler displacement concept. After successful results had been obtained, the concept was validated on a fast Fourdrinier pilot machine, which is more representative of a commercial paper machine.

On the slow Fourdrinier machine, clay suspensions of 1, 10, 100, and 200 g/L were applied to the wet paper from the secondary headbox. Some clay was treated with PEI (1 mg/g of clay) to reduce the surface charge and promote fiber−clay interactions. In addition, a few PEI solutions at a concentration of 1 mg/g of fiber were passed through the sheet to demonstrate that polymers can also be retained in this way. The clay that passed through the sheet was collected in a separate drain and was not mixed with the whitewater in the wire pit, which was used to dilute the pulp to the desired consistency.

On the fast machine, paper was made from unbleached kraft at 1% consistency, and no retention aids were used. It took about 100 s for the PCC pigment to reach the slice of the secondary headbox after the valve from the feeding tank to the secondary fan pump had been turned on. A PCC pulse of about 1 min was applied. If mixing had been perfect, the maximum concentration of PCC applied from the secondary headbox would have been 160 g/L (in most cases). However, because of turbulence created by the fan pump, the 1-min pulse resulted in a varying secondary headbox concentration lasting for several minutes, with a maximum concentration reaching about one-half of the target concentration. Therefore, the secondary headbox concentrations could not be preset. Instead, samples were taken for each run, and the concentrations were determined by drying and weighing. They varied from 10 to 115 g/L. Samples of the corresponding paper after the press were collected and dried off-line. The PCC used in the experiments was untreated, treated with cationic starch (10 mg/g PCC), treated with PEI (1 mg/g PCC), or treated with an anionic stabilizer (5 mg/g PCC). Also, PEI and starch solutions at dosages of 1 and 10 mg/g of fibers, respectively, were passed through the wet sheets. When required, the starch and PEI contents of the sheets were determined by an enzymatic reaction and the Kjeldahl method, respectively.

Results for the Slow Fourdrinier Machine

The addition of clay to paper resulted in the expected increase in basis weight. The results for untreated clay showed a linear increase of basis weight with clay content, from 85 to 110 g/m^2, with clay contents up to 25%.

Figure 4 shows how the ISO opacity and brightness vary with clay content for papers containing either untreated or PEI-treated clay. No statistically significant differences were found between the brightness from

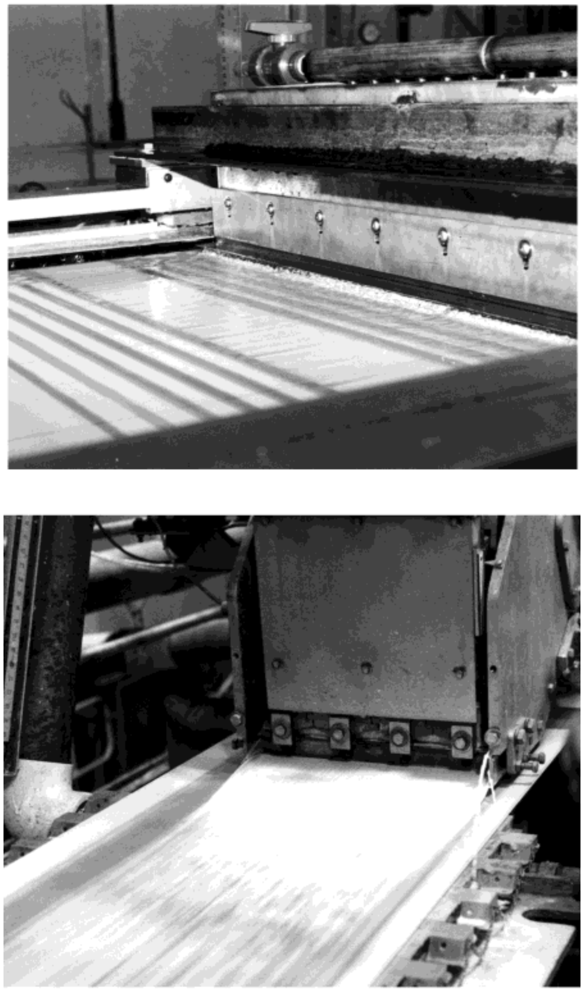

Figure 3. Photographs of a filler suspension flowing out of the secondary headbox onto wet paper on a slow Fourdinier macine (top) and a fast Fourdinier macine (bottom). The locations of the two drylines is consistent with the predictions of eq 3.

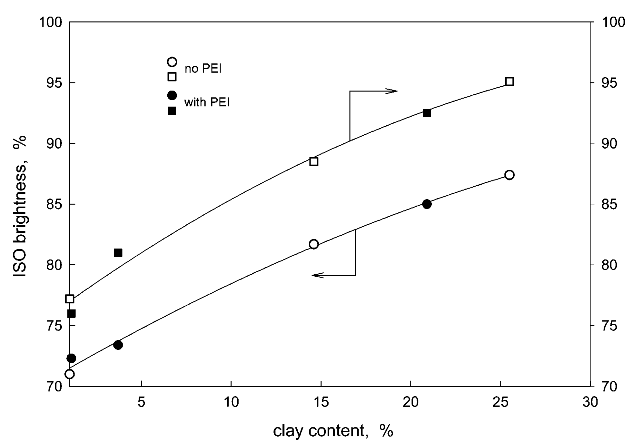

Figure 4. ISO brightness and opacity for papers filled with clay from the secondary headbox.

the topside and the wire sides of the sheets. It can be seen that both brightness and opacity increase with increasing clay content. Furthermore, the optical properties of the sheets filled with treated and untreated clay seem to be identical.

Figure 5. shows the TEA (total energy absorption) as a measure of the strength of the sheets. The control is the paper sheet made from the primary headbox, with no water from the secondary headbox passing through it. Blanks (fibers only) for the fast machine (see Figure 11 below) do fall on the same curves as filled sheets, implying that passing water through a sheet does not affect strength. It can be seen that, for low filling levels (about 2%), the strength of the sheet increases, whereas for high filler levels, the expected trend is found, namely, a decrease in strength with increasing clay content.[11] The increase in strength at low filling levels could be caused by the low probability that clay particles would deposit in locations where they would interfere with interfiber bonding during drying. Some of the clay particles could strengthen the sheet by forming a bridge between fibers that otherwise would not be linked. In this respect, clay particles can act similarly to bentonite, which is used, in combination with cationic polyacrylamide, as a retention aid system to increase the bond strength between particles.[12] Also included in Figure 5 are the results for sheets to which PEI was added (without clay). It was found that PEI addition resulted in strengthening of the sheets. Attempts to measure the amount of PEI by the Kjeldahl method were not very accurate because of a significant nitrogen background from the fibers themselves, but estimates suggest that close to monolayer coverage must have been present. This observation suggests that it might be advantageous to add strength agents to wet paper by this method.

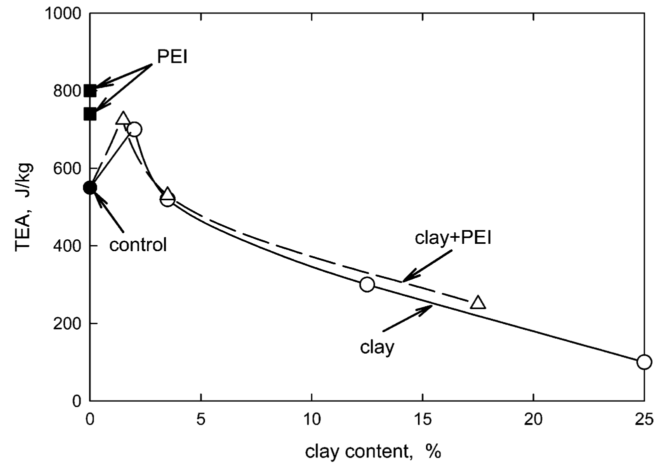

Figure 5. Total energy absorption of wet-filled sheets as a function of clay content.

SEM images of highly filled sheets show that clay fills the space between the fibers, but little or no deposition of clay on the fibers occurred. This is to be expected, as clay and fibers are both negatively charged. In treating clay with PEI, insufficient PEI was added to reverse the charge of the clay; instead, PEI induced clay flocculation. For highly filled sheets, the topside and wire side exhibit similar surface characteristics, whereas for lower filler levels, more clay was observed at the topside than at the wire side, similar to the filling of stationary sheets[7] and the filling on a fast Fourdrinier machine (see below).

Results for the Fast Fourdrinier Machine

Large amounts of PCC could be retained in the sheet by filling wet paper. Figure 6 shows the retention for PCCs treated in various ways and for various PCC dosages. The highest loading obtained was more than 35%, which was found for the addition of nearly 45% PCC treated with cationic starch. Interestingly, untreated PCC can be successfully retained in the sheet

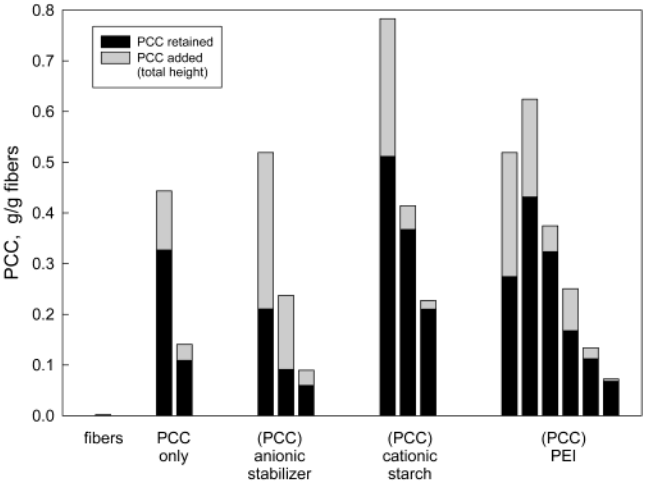

Figure 6. Retention of PCC in paper (black bars). The total bar height corresponds to the amount of PCC added. The parentheses refer to PCC treatments with polymers. The different bars are for various runs with different secondary headbox concentrations (proportional to the addition levels shown in the figure).

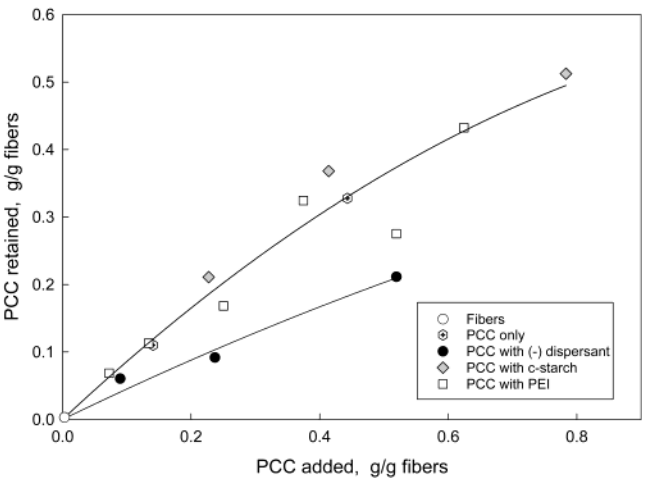

Figure 7. Relation between retained and added PCC for positive and negative PCCs.

without the use of retention aids. Also, the strongly negative PCC that was treated with the anionic stabilizer can be retained in the paper using this filling method. The reason is that the fillers remain in the water in the sheet after pressing and, during drying, they collapse onto the fibers. It is of interest to note that the added amounts are consistent with those required for full water displacement. Assuming a typical solid content of 10−15% at the dryline,[10] then for each gram of fiber, 8.5−9 g of water is present. However, about 1 g is associated with the fiber wall, and another 1.5−2 g of water is inside the lumen, leaving about 6 g of water in the interfiber space in the sheet. At the highest addition of 115 g/L PCC, a displacement of 6 cm^3 of water per gram of fiber results in a filling of about 0.7 g/g, which is close to filler addition (0.78 g/g). Because the flow rate from the secondary headbox was constant, the same water displacement occurred for all runs.

To better illustrate the retention of pigment in the paper, the amount of retained PCC was plotted against the amount of PCC added (Figure 7). The retentions of positive calcium carbonate fillers, whether untreated or treated with cationic polymers, followed the same pattern. It seems that, when PCC that had a positive surface charge, it could deposit onto fibers through

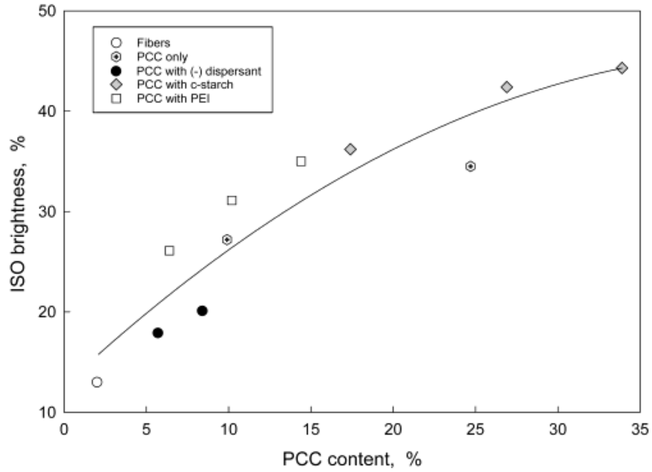

Figure 8. ISO brightness of topsides of sheets as a function of PCC content.

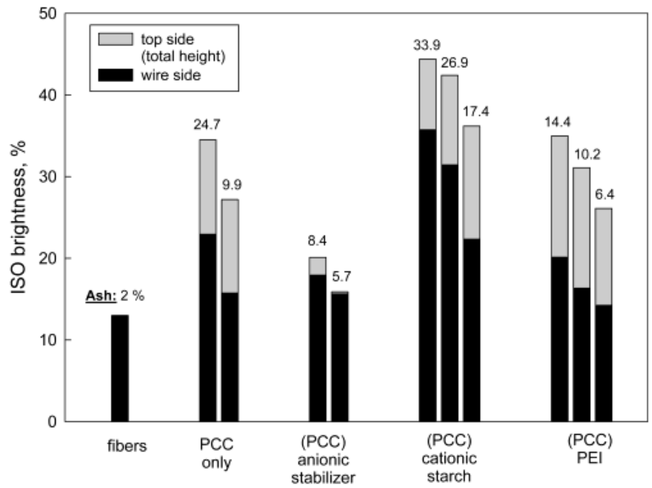

Figure 9. Comparison of brightness on top and bottom sides of sheets filled with various amounts of PCC, treated in various ways. The parentheses refer to PCC treatments with polymers.

electrostatic attraction. The origin of the positive charge seemed to have no effect on the deposition. This shows that PCC retention was mainly driven by the electrostatic attraction between positive fillers and negative fibers. In contrast, when negatively charged PCC was used, the retention was much lower, although filling levels of up to 17% were obtained. The filler that was not retained in the paper went through the wire to the suction boxes, and the rest was squeezed out in the press section of the machine.

The ISO brightness of the sheet increased with increasing filler content as expected. These results are presented in Figure 8. The treatment of PCC with various polymers had little effect on the ISO brightness. The scatter in the data could be due to different degrees of filler flocculation in the sheet caused by the different surface treatments. To better appreciate the effects of surface treatment and also the degree of two-sidedness, the ISO brightness results for the various PCCs are plotted in Figure 9. It can be seen that all sheets (except the blank) exhibited two-sidedness. The largest two-sidedness was found for sheets with cationic PCC, but the two-sidedness diminished with increasing filler content. The two-sidedness of sheets filled with negative PCC was surprisingly low. One sample with 5.7% PCC exhibited negligible two-sidedness. The trend in two-sidedness agrees with the findings in stationary sheets.[7]

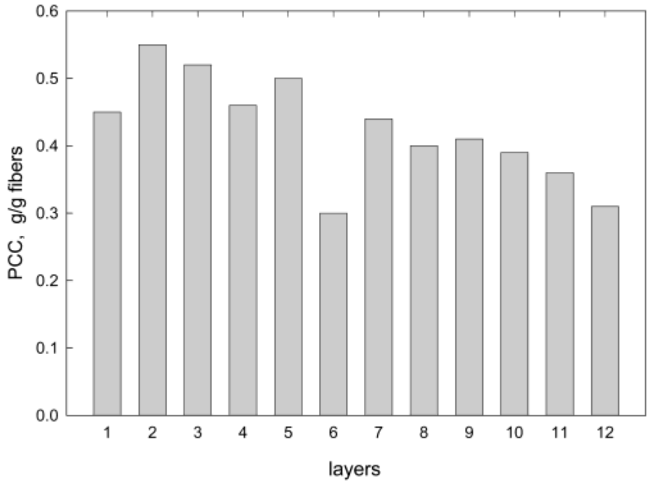

Figure 10. Concentration of starch-treated PCC throughout the sheet. The sheet was divided in 12 layers by peeling. Layer 1 is the top layer; layer 12 is the bottom layer.

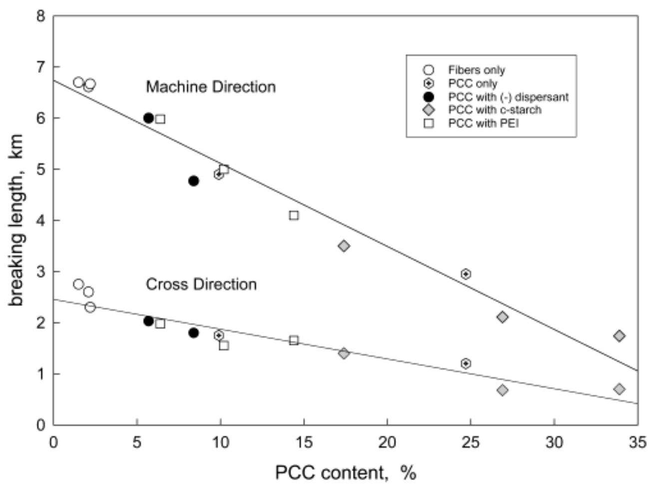

Figure 11. Breaking length of PCC-filled sheets as function of PCC content, in both the machine and cross directions.

The differences between cationic and anionic fillers are due to kinetic effects: the topside is exposed to fillers for a longer time, and more filler deposition on the fibers takes place. No such deposition occurs for negative fillers. Some filtration of the pigment on top of the sheet could also possibly occur.

The two-sidedness was further tested by peeling off individual layers of the sheet and determining their ash content at 550 °C. The results are presented in Figure 10. Interestingly, the first layer did not exhibit the highest pigment content. Nevertheless, there was a gradual decrease in PCC concentration throughout the sheet, responsible for the two-sidedness in brightness. Layers 1 and 6 did not follow the downward trend, probably because of experimental error. Given that the top layers did not have excessive amounts of PCC, this is a good indication that retention of the pigment by filtration was not a factor.

The strength of the sheets was determined, both in the machine direction and in the cross direction. The strength is expressed in terms of breaking length, which follows trends similar to those exhibited by TEA. The results are shown in Figure 11. For the same PCC content, the sheet was almost three times stronger in the machine direction than in the cross direction. The treatment of PCC with polyelectrolytes had no effect on paper strength. The treatment of fibers with PEI or

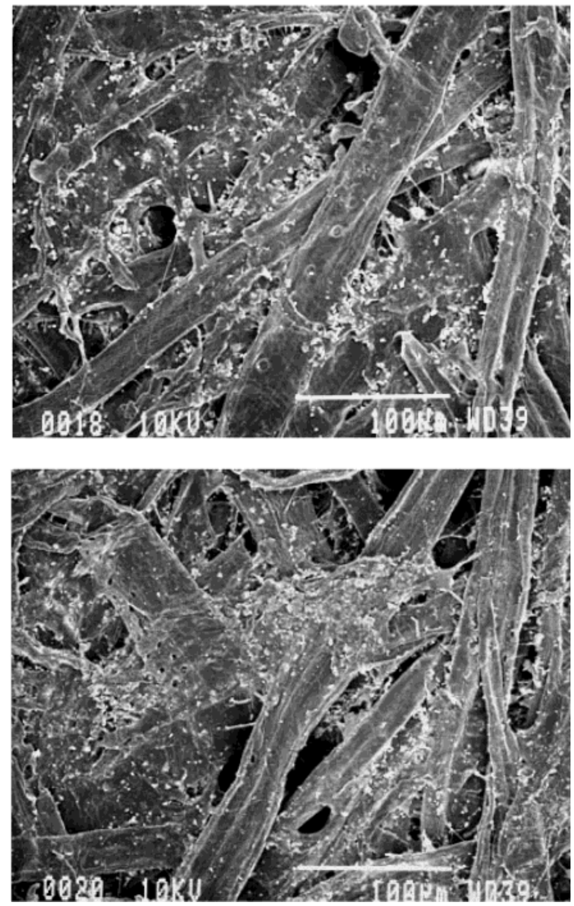

Figure 12. SEM images of top and bottom sides (top and bottom images, respectively) of sheet filled with anionic PCC. The PCC content is 8.4%.

cationic starch showed no increase the strength, which is in contrast to what was seen on the slow Fourdrinier machine (cf. Figure 5). Because the unbleached pulp was refined to 550 mL CSF, the tensile strength of the paper was much greater than for the slow Fourdrinier machine, where unbeaten pulp was used. The contribution of the PEI or cationic starch to the tensile strength of an already very strong sheet is therefore insignificant. Given that we do not have data for low degrees of loading (around 1%), because of the difficulty in presetting PCC concentrations in the secondary headbox (cf. Pilot Paper Machines section), we could not find an initial increase in strength for small loading levels. It is also possible that PCC acts differently than clay, because of their different shapes (round vs platelike).

As mentioned earlier, determining the PEI concentration in the sheets was difficult, because of high background levels of nitrogen from nitrogen-rich compounds in the fibers. For sheets to which 10 mg/g of starch had been added, enzymatic starch determination showed that 70% of the starch was retained, which corresponds to about a monolayer of starch on the fibers.[13] These examples demonstrate again that polymers can be incorporated in wet sheets as well.

Finally, the sheets were examined by scanning electron microscopy (SEM). Figure 12 shows the top and bottom sides of a sheet containing PCC treated with anionic polymer. It can be seen that the two sides look very similar, which is in agreement with the low two-sidedness seen in brightness (cf. Figure 9). Figure 13 shows SEM images of the top and bottom sides of paper highly filled with PEI-treated PCC. These papers show

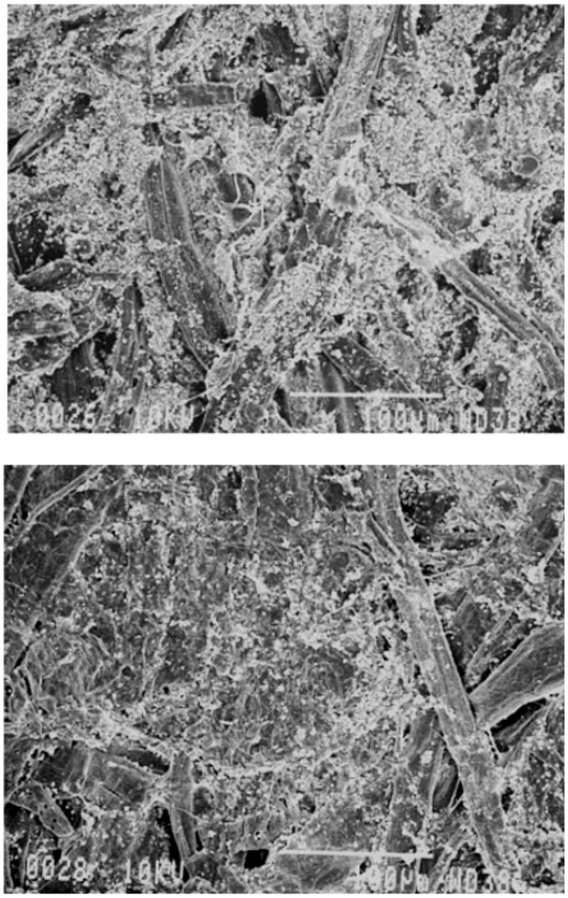

Figure 13. SEM images of top and bottom sides of sheet filled with PEI-treated PCC. The PCC content is 14.4%.

a two-sidedness that tends to diminish at higher filler content. Sheets filled with clay showed a trend in two-sidedness similar to that of sheets filled with PCC, indicating that the speed of the machine has little effect on the filler distribution in the sheet.

Concluding Remarks

The pilot trials described herein were a success in many ways. They demonstrated that paper can be filled with clay or PCC by applying a concentrated filler suspension to a sheet of paper, with the use of a secondary headbox placed near the dryline of a Fourdrinier paper machine. Filler contents of up to 35% were obtained. Both positive and negative fillers can be incorporated in the sheet, with or without a retention aid. Loading levels are higher for positive fillers, but at the cost of a greater two-sidedness. The two-sidedness decreases with increasing loading level. For negative fillers, two-sidedness is negligible. Also, polymers can be incorporated into paper this way as well.

The presence of pigment had a detrimental effect on the paper strength. Thus, the assumption that paper made in this way would be stronger than conventionally filled paper because of a reduced probability that fillers would enter spaces between fibers that are in a favorable positions to bond was found to be invalid.

Acknowledgment

The authors thank André Leger, Michel Farell, Dr. Bob Alince, Rick Collins, and Louis Godbout for their help in the pilot trials. The help of Jean Paradis (CSSP) and Marc Foulger (GL&V) and the donation of clay by ECC (now IMERYS) and PCC by Specialty Minerals are gratefully acknowledged.

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Received for review October 24, 2003
Revised manuscript received February 4, 2004
Accepted February 23, 2004

IE034203I