

# *Forming fabric weave-scale variations in paper filler content*

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**ABSTRACT:** A series of experiments were conducted on handsheets to investigate small-scale variations in filler concentration on the surface of paper. The surface distribution of two types of filler material was investigated: precipitated calcium carbonate ( $\text{CaCO}_3$ ) and kaolin clay ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ). The effect of retention aids, dewatering rate, and forming fabric geometry on filler distribution was tested. Local filler concentration was found to be strongly correlated with the relative flow velocity during formation. In samples formed by gravity and vacuum drainage, kaolin displayed a significantly greater variation in local concentration than precipitated calcium carbonate, though the difference was reduced under vacuum drainage conditions. The distribution on the top side of the paper was comparable between the filler types, independent of drainage velocity. Under vacuum drainage, retention aids did not improve filler uniformity on the wire side. However, on the top side of the paper, a moderate reduction in spatial variation was observed. Additionally, on the wire side of samples made with gravity drainage, the addition of retention aids produced a significant improvement in the uniformity of the filler material. These filler distribution trends are believed to be related to variable filler retention as a function of filler type, drainage velocity, and chemical retention aids. Additionally, samples made with an industry forming fabric showed the same distribution trends and an improvement in the uniformity of the filler material.

**Application:** This is the first paper to show that the forming fabric structure affects filler distribution, which presumably affects printability. Forming fabric manufacturers can benefit from this information, as it is another factor to be considered in fabric design.

**D**uring papermaking, filler material is not uniformly deposited throughout the paper sheet. This variability in concentration can greatly affect the properties of the product, and consequently, different distribution patterns are developed in the paper depending on the desired end use. For example, copy paper requires surface filler content lower than the average filler content to reduce dusting. In contrast, supercalendered paper, inkjet printing paper, and coated paper require high concentrations of filler material on the surface, but do not need similar levels in the center [1-3].

In general, additional filler material increases the surface quality of paper by increasing brightness and reducing roughness, which creates a desirable printing surface [1]. Small filler particles tend to fill the larger pores in the paper surface, which are the main cause of misprints in rotogravure printing [2]. Additionally, a high concentration of filler material on the surface of the paper reduces the penetration of the ink into the paper, an undesirable effect called “ink strike through” [3]. In high quality printing applications, misprints and ink strike through should be minimized, which can be accomplished with higher surface filler concentration levels.

Filler distribution in the z-direction of the paper has been studied extensively, and it has been shown that dewatering conditions are mainly responsible for the migration of fines

and filler material [4-6]. The filler distribution through the paper thickness tends to be characteristic of the type of former used. For example, with a fourdrinier former, the pressure pulses remove filler from the paper wire side, leaving a higher filler concentration on the top side [1]. In a twin wire former, where water is removed from both sides, the distribution is close to symmetric, and in a handsheet former, where the dewatering rate is slow, filler tends to be concentrated toward the wire side [7,8]. Previous work has been conducted to investigate the uniformity of paper surface material and the effect on printing, as well as the z-direction filler distribution towards the surface [2,3]. The current work is focused on forming fabric weave-scale variation in filler concentration on the surface of the paper.

Filler and fine particles are retained in paper through a combination of adsorption, filtration, sedimentation, and flocculation [9-11]. Most of the deposition of the filler material onto pulp fibers occurs in the headbox as a result of electrostatic bonding [4,6,12], but a portion of the deposition occurs during the drainage of white water from the wet mat [11]. Through pressing tests, it was concluded that three of the main factors affecting filler distribution through the thickness of the paper are drainage flow velocity, filler content, and particle size [6]. Additionally, it has been experimentally and numerically shown that the geometry of the forming fabric af-

fects the drainage flow field around the fabric and has a significant effect on the localized z-direction flow velocity [13,14]. Peng and Green showed experimentally that upstream of the forming fabric, the z-directional flow velocity is at a maximum over openings in the forming fabric and at a minimum over the knuckles. In addition, the flow becomes more uniform with distance from the fabric [13].

We hypothesize here that the local flow field affects the distribution of the filler material on the paper surface. We propose that as water is drained from the wet web through the forming fabric, filler material will tend to be concentrated in the regions of higher flow rate, and therefore predict that the mat formed over openings in the fabric will contain the most filler material, the regions corresponding to the threads of the fabric will contain less, and the paper formed on the knuckles will contain the least filler. We test this hypothesis in the current research by studying the small-scale variations (on the level of individual strands of the fabric) in surface filler concentration. We speculate that these repeating, small-scale variations in filler concentration are relevant as they may lead to repeating regions of lower ink density, which may be apparent in printed paper.

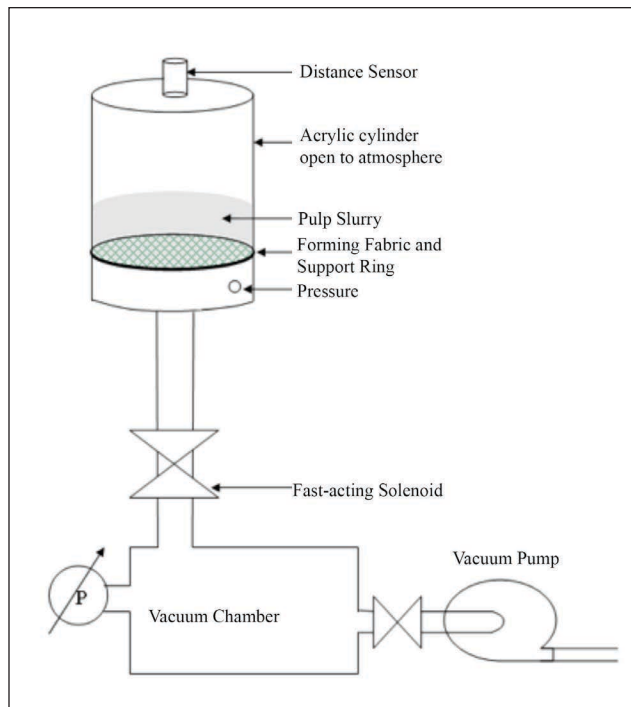
Pulp fibers are anionic in a suspension, so the charge of the filler material will determine whether it experiences an electrostatic attraction or repulsion from the pulp [15-17]. We hypothesize here that an electrostatic attraction between the filler and fibers will tend to reduce the variation in concentrations on the paper surface because the filler is bonded to the fibers and not free to move with the flow field. This hypothesis is tested in the current research by comparing samples made with two different filler types.

## MATERIAL AND METHODS

### Experimental specifications

Surface filler concentration was tested with handsheets made using a custom laboratory apparatus that is similar to a handsheet former. **Figure 1** shows a schematic of the apparatus. The device consists of an airtight vacuum chamber that acts as the base. This chamber can be opened to the atmosphere or closed and given a negative gauge pressure with the use of the vacuum pump. Extending vertically from the vacuum chamber is a 75 mm diameter acrylic cylinder, which is separated from the vacuum chamber by an electronically actuated solenoid valve. On top of the cylinder is a horizontal flat plate that supports the forming fabric and the pulp chamber. The fabric is secured in place between the flat plate and pulp chamber and is encircled by a gasket to provide an airtight seal.

A pressure transducer is mounted flush to the pipe wall immediately below the forming fabric to measure the pressure drop across the fabric. An ultrasonic distance sensor is mounted above the upper pulp chamber. The sensor measures the height of the pulp suspension as a function of time, the values of which can later be used to calculate the drainage rate of the water through the forming fabric.



**1. Handsheet former schematic.**

To make a paper sample, the lower acrylic pipe is filled with distilled water from the closed solenoid to the level of the forming fabric. The desired forming fabric is fitted in place and the upper pulp chamber is attached. A quantity of pulp suspension that corresponds to the desired basis weight of the paper sample, based on the amount of dry material in the suspension, is measured out. If gravity drainage is desired, the vacuum chamber is opened to the atmosphere. If an applied suction is desired, the vacuum pump is activated to bring the pressure in the chamber to the required value. The pulp suspension is then transferred to the top chamber.

A LabVIEW program (National Instruments; Austin, TX, USA) starts the process by triggering the solenoid, as well as simultaneously recording the pressure and distance sensors. With the solenoid valve open, the water from the pulp suspension drains through the forming fabric, and into the vacuum chamber. A fiber mat is formed on top of the forming fabric. The LabVIEW program automatically closes the solenoid after 10 s, ending the experiment. The voltage signals from the distance and pressure sensors are put through a low pass filter and saved for further analysis. The samples are then left to air dry in contact with the forming fabric before further processing.

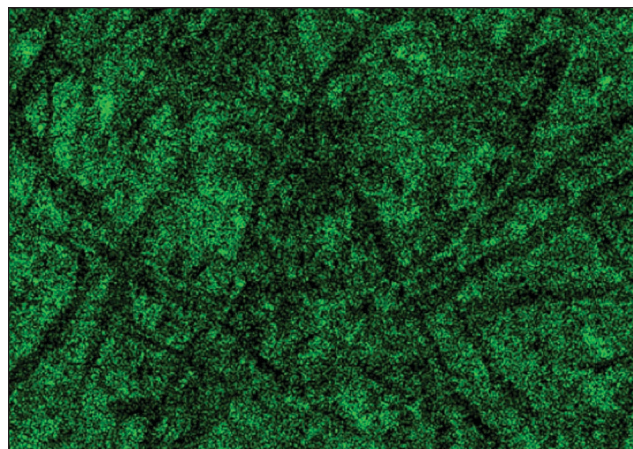
All samples made for these experiments used softwood, hydrogen peroxide-bleached (to 72% ISO brightness) thermo-mechanical pulp. The fraction of fines that passed a P200 in a Bauer-McNett classifier (Frank-PTI; Birkenau, Germany) was 30.1%. The pulp suspension was made by mixing 80 g of the dry materials into 3200 mL of distilled water at 80°C. The suspension was mixed at 3000 rpm for 7.5 min, and then diluted

to 0.5% consistency by adding distilled water. The pulp suspension was refrigerated when not in use. When making a sample, the suspension was continuously stirred at room temperature, creating a uniformly dispersed mixture with a sampling error less than 1% [15]. Samples were made at a basis weight of 60 g/m<sup>2</sup>.

Two types of filler were used, both at a loading of 40% of the dry mass. The first was a precipitated calcium carbonate (PCC) made by Specialty Minerals (New York, NY, USA). This PCC has a scalenohedral particle shape and a volume-weighted mean particle size of 5.4 µm. Dispersed in distilled water, it is cationic, with a charge of +0.1 µeq/g [16]. The second filler was ground kaolin clay (Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>) with platelet shaped particles and a mean volume-weighted particle size of 10.8 µm. Dispersed in distilled water, the anionic kaolin carries a charge of -1.7 µeq/g [15]. Although the particle sizes in the two fillers are different, both are smaller than a typical fiber mat pore size, so it is unlikely that this difference would have had a significant effect on retention [11].

Water was drained from the suspension, through the fabric, by gravity drainage (which was accomplished by opening the vacuum box to the atmosphere) or with an applied suction of approximately -33.9 kPa (through the use of the vacuum pump). The drainage velocity was in the range of 0.03 m/s under gravity drainage and 0.12 m/s in vacuum drainage. Retention aids consisting of a combination of a cationic polyacrylamide (cPAM) and silica microparticles were used in some experiments; 0.35 kg of cPAM and 0.5 kg of silica were used per ton of pulp.

Handsheets were formed on two different forming fabrics, both supplied by AstenJohnson (Charleston, SC, USA). The



**2. Preliminary energy dispersive X-ray spectroscopy scan of precipitated calcium carbonate sample.**

first is a plain weave (2 harness, 1/1 twill), single layer fabric that is not used in industry. This was chosen to create the simplest drainage flow field. **Table I** shows the fabric specifications. The second fabric is a trademarked single layer fabric, Monoflex (5 shaft), the properties of which are listed in **Table II**.

### Data collection and analysis

The elemental composition of the paper surface was determined using scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) techniques. The techniques have been shown to work successfully in previous studies of the elemental composition of paper [17-19]. EDX is particularly well suited to this work because it gives the spatial location and concentration of all elements present in the sample surface. The surface data are recorded and presented with XOne X-ray microanalysis software (Quartz Imaging; Vancouver, BC, Canada) as a spatial intensity map with a resolution of 480 × 640 pixels. The intensity of the pixels directly corresponds to the concentration of the element of interest [20-22]. By plotting the elemental maps of atoms only present in the filler material, the location and concentration of the surface filler can be seen. In the case of PPC filler, calcium is plotted, and with kaolin, the same is done for a combination of aluminum and silicon. The pixel intensities in the elemental maps produced by the software are not linearly correlated to the local atomic concentration; they are skewed for improved viewing, so for the analysis, the raw data were used.

Paper samples were separated from the forming fabric and imaged. An initial EDX scan of a PCC filled paper sample produced the calcium map shown in **Fig. 2**. Black pixels represent regions of the sample where no calcium was detected. Green pixels contain calcium, and the brightness of the pixel is positively correlated with concentration.

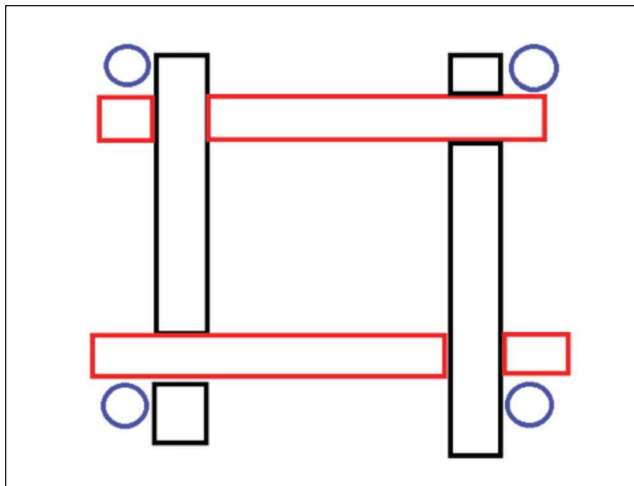
As seen in Fig. 2, the location of the surface fibers is clear (the black lines) and the filler material tends to be clustered between the fibers. However, because there is no clearly visible distribution pattern, we realized that if the flow field was

|                                            | Machine Direction | Cross-Machine Direction |
|--------------------------------------------|-------------------|-------------------------|
| Thread center line to center line distance | 841 µm            | 864 µm                  |
| Thread thickness                           | 285 µm            | 313 µm                  |

### I. Dimensions of coarse plain weave forming fabric

| Product name                                         | Monoflex (5-shaft) |
|------------------------------------------------------|--------------------|
| Number of layers                                     | 1                  |
| Machine direction yarn diameter                      | 0.16 mm            |
| Cross machine direction yarn diameter                | 0.19 mm            |
| Paper side weave                                     | 1, 4 broken twill  |
| Air permeability at 125 Pa – cfm (m <sup>3</sup> /s) | 570 (0.269)        |
| Fiber support index (FSI)                            | 146                |
| Drainage index                                       | 54.4               |

### II. Specifications of fine plain weave forming fabric.

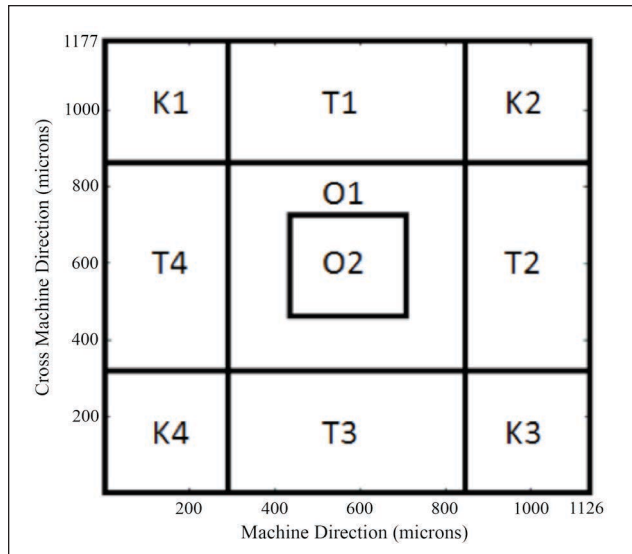


**3. Schematic of pinhole approach.**

influencing the distribution of the filler material, the effect was being masked by the deposition of the fibers. Additionally, the wire mark was not apparent in this scan, so it was not apparent which regions of the forming fabric were associated with which sample areas. Consequently, a method was developed to identify the regions of the paper in the EDX scan, and to minimize the noise created by the fiber deposition, in the hope that an underlying distribution trend would emerge.

The principal focus of the work was to determine how the geometry induced flow field affects the surface filler distribution; therefore, a sample was designated as the area of paper formed over one repeat in the geometry of the fabric. To locate this area in the EDX, samples were dried in contact with the fabric, and then pinholes were made in the paper, surrounding the region formed over one repeat of the geometry. **Figure 3** shows a schematic of the approach. **Figure 4** shows an SEM image and corresponding EDX scan of the result. The sample area is bounded by the four holes seen in Fig. 4.

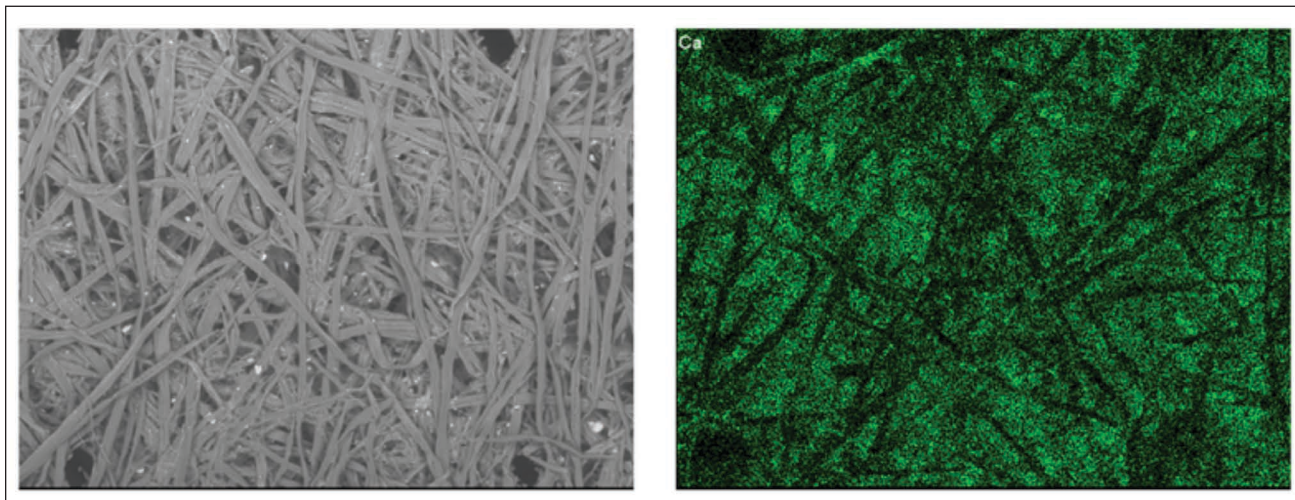
The sample area was clearly visible in the EDX scan (Fig. 4),



**5. Zoning pattern for sample analysis.**

but there was no clear distribution pattern. The results varied considerably between samples because of the orientation of the surface pulp fibers. An analysis method was developed to average the intensity values of the pixels over like regions of the paper to effectively reduce the resolution of the data, and thus increase the effective signal-to-noise ratio. The SEM was used to measure the dimensions of the forming fabric. With this information, it was determined which portions of the EDX scan represent the different regions of a paper sample. The sample area was divided into a series of zones (**Fig. 5**).

In this scheme, the zones correspond to the geometry of the fabric. Thus, the zones K1-K4 represent the regions of the paper formed on the fabric knuckles. Similarly, zones T1 and T3 contain the paper formed over the machine direction threads, and zones T2 and T4 are the cross-machine direction threads. The area of paper formed on the opening in the fabric is represented by the two concentric rectangles, O1 and O2,



**4. Scanning electron microscope image of sample area (left) and corresponding energy dispersive X-ray spectroscopy scan (right).**

giving additional detail on the variation across the opening.

The samples were analyzed with the MATLAB (Mathworks; Natick, MA, USA) image processing toolbox. The mean intensity value for all the pixels within each zone was calculated, as well as the mean intensity value for the entire sample. The mean zone intensity was then normalized with the mean sample intensity. This research is focused on variations in filler distribution across the paper surface. By normalizing the pixel intensities, this requirement was met, with the added benefit of allowing for comparison between samples with different absolute filler concentration values. The intensity values of the pixels were averaged over a large area to minimize the noise from random fluctuations between samples, but further measures were required for an underlying trend to emerge. The normalized values were averaged between similar zones. Because all the knuckles experience approximately the same flow conditions, and could be expected to converge on the same relative filler concentration value, all K intensity values were averaged together. The same was done for the threads. These values were then averaged across 36 samples for each experimental case. Once this significant noise smoothing was completed, a mean distribution of the concentration of the filler material could be seen.

## RESULTS AND DISCUSSION

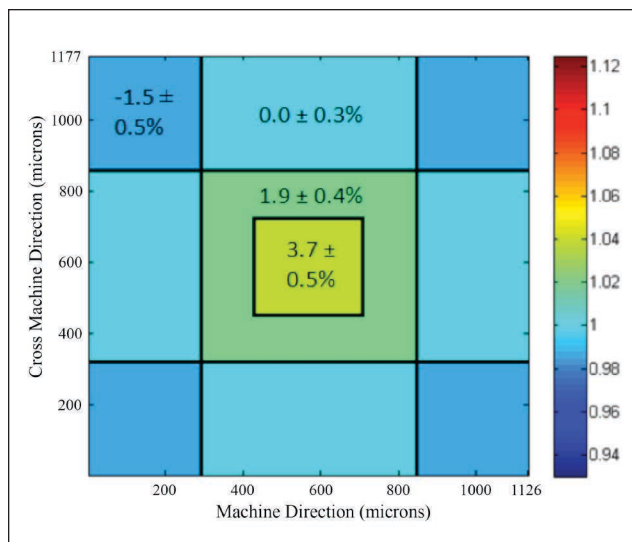
Results are represented as thermal maps of the zoning pattern (Fig. 5). The numbers in each zone show the normalized amount of filler material, as a percentage above or below the mean sample value, as well as the standard error of the data. Thus, for example,  $-1.5 \pm 0.5\%$  in the top left corner of **Fig. 6** indicates that the fiber mat formed over the knuckle has an average filler concentration 1.5% below the mean filler concentration, and the standard error of this value was 0.5%.

### Effects of filler type under gravity drainage

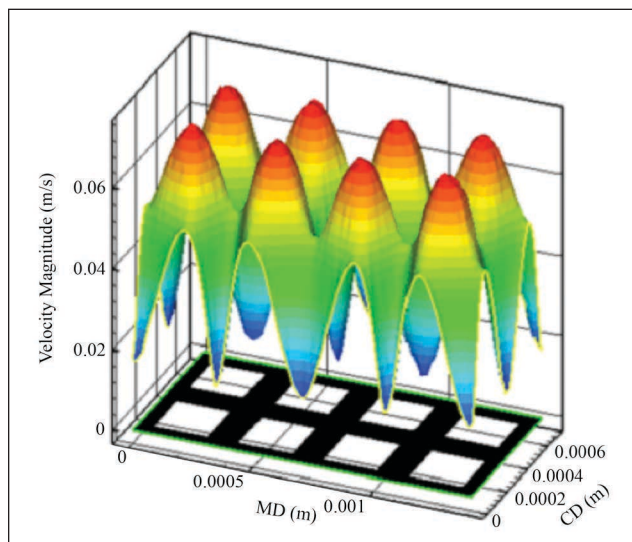
The first set of experiments aimed to examine the effects of filler particle charge by comparing the variation in surface filler concentration observed in samples made with PCC and kaolin filler. Filler was added to the suspension at 40% of the dry mass component. To isolate the effects of the filler material, no retention aids were used, and the water was drained through the fabric by gravity. Figure 6 shows the results from the analysis of the wire side of PCC samples.

The areas representing the paper formed over the top of the knuckles of the forming fabric have the lowest filler concentration of all the zones. These areas are below the average level for the whole sample by 1.5%. The areas of the paper formed over threads do not differ from the mean sample filler concentration level. Conversely, the outer square of the interior region, which corresponds to the outer area of the paper formed on top of an opening in the forming fabric, is above the mean filler concentration by 1.9%, and the innermost area has 3.7% more PCC than the mean. These differences were all found to be statistically significant, at a 95% confidence level.

Computational fluid dynamics (CFD) was used to compute



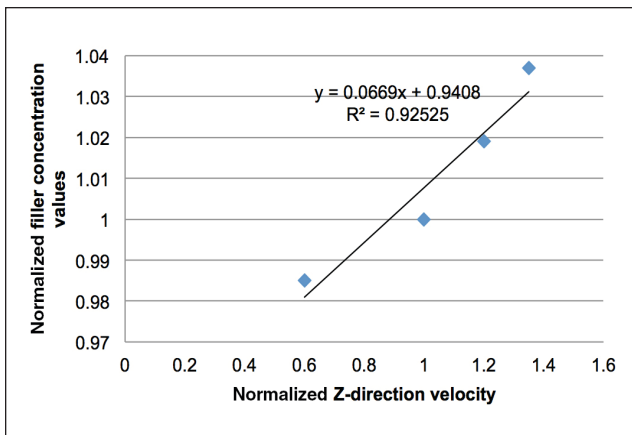
**6. Precipitated calcium carbonate filler distribution for wire side gravity drainage case.**



**7. Z-direction velocity through forming fabric [23].**

the single phase flow field in the vicinity of a fabric, at a Reynolds number approximately matching that of most experiments. The fabric used in the simulations was topologically identical to the experimental fabric, but with slight geometric variations owing to manufacturing processes. **Figure 7** depicts the z-component (through-fabric) velocity at a height of  $0.25d$  ( $32.5 \mu\text{m}$ ) above the plane of the top of the fabric. The velocity has the highest magnitude through the centers of the openings, and drops off to a minimum over the knuckles of the fabric. Figures 7 and 6 show good correlation between the regions with elevated filler concentration and the regions with high z-component velocity. This initial result was extremely important because it supported the hypothesis that regions of the paper formed in areas of high flow velocity would tend to contain the most filler material.

**Figure 8** shows the percentage variation from the mean



**8. Regional comparison of normalized filler concentration and z-direction flow velocity.**

of the filler distribution by region, plotted against the percentage variation from the mean of the z-component of velocity. From left to right in Fig. 8, the data points represent the regions formed over the knuckles, threads, outer opening, and inner opening, respectively. The correlation coefficient of the least-squares fit to the data is 0.93; the filler distribution and z-component of velocity are highly correlated. Although these two variables are well correlated, the least-squares line slope is much lower than 1.0. We believe that a main reason why a 7% increase in z-component of velocity leads to only a 1% increase in the local filler content is the limited mobility of filler particles. If filler particles are intimately bound to long fibers, which move negligibly in response to the hydrodynamic forcing, then the filler particle distribution will be uncorrelated with the local fluid flow. A second reason for the low slope of the line in Fig. 8 is that the fluid flow through a fiber mat adhering to a forming fabric is strongly affected by the fiber mat. Once 5-10 g/m<sup>2</sup> of fiber has built up on a fabric, for example, the flow field through the fiber mat is almost spatially uniform [24-26].

Throughout the following results, the percent difference between the zones with the least and most filler material was used to quantify the level of concentration variation. This value has been termed the maximum difference and is equal to 5.2% in this case. Next, the top side of the PCC samples and the wire and top side of the clay samples were investigated. **Table III** summarizes the results for both PCC and clay filler.

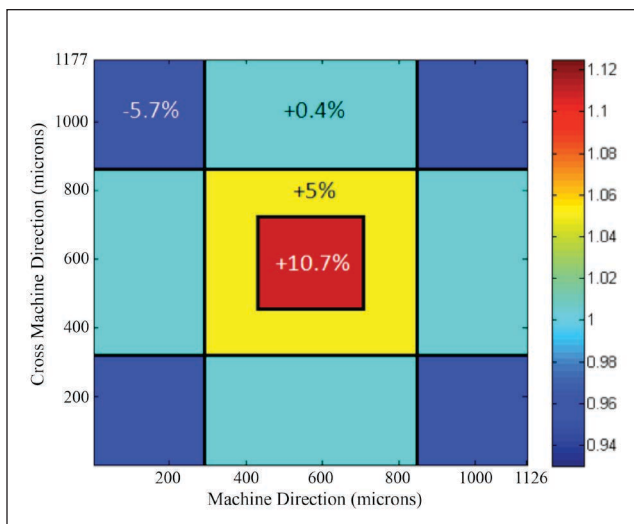
The columns in Table III show the relative amount of filler material in each zone for the four cases. There are several interesting points to note. First, for the top side PCC case, the general trend of the filler distribution is the same as on the wire side, but the magnitude of the variation is considerably less. The maximum difference on the top side is 1.3%, compared to the 5.2% seen on the wire side. The knuckles and inner opening remain the zones with the least and most filler material, respectively. The top side filler observations further support the hypothesis that the filler concentration variation is directly related to the variations in the flow field. The flow field forming the paper on the top side is significantly more uniform than the flow field on the wire side. This is a result of the greater distance from the geometry of the fabric, and because the flow is passing through the relatively uniform fiber mat [13,14].

The wire side clay samples demonstrate the same distribution trend as the previous samples, but the variation is much greater than on the wire side of the PCC samples. The maximum difference more than doubled with the clay filler. As stated previously, the filler deposition is largely linked with the placement of the pulp fibers, resulting in a relatively uniform distribution. The level of filler mobility relative to the pulp fibers should correlate with the variation in filler distribution in the finished sheet. Cationic PCC filler particles tend to bond to the anionic pulp fibers, which allows the PCC particles to resist, to some extent, the effects of the flow field. The filler deposition is linked with the placement of the pulp fibers, resulting in a relatively uniform distribution. In contrast, with the anionic clay filler, it is thought that the clay particles do not bond to the pulp fibers, so the deposition is governed much more heavily by the flow field, thereby giving a more varied surface concentration with clay filler. Note also that the clay particles are twice the size of the PCC particles, and thus should have reduced mobility within the fiber matrix. The fact that the clay particles show greater responsiveness to the flow field is evidence that the charge of the filler particles, not their size, is the determining factor in their spatial distribution near the fabric.

The analysis of the top side of the clay samples yielded interesting results in that the distribution did not increase from the PCC case in a similar ratio to that seen between the wire side results. On the top side, where the flow field is more uniform, the filler charge appears to make less difference on the

| Sample         | Knuckle | Thread | Outer Opening | Inner Opening | Maximum Difference |
|----------------|---------|--------|---------------|---------------|--------------------|
| Wire side PCC  | -1.5    | 0      | 1.9           | 3.7           | 5.2                |
| Top side PCC   | -0.5    | 0.1    | 0.5           | 0.8           | 1.3                |
| Wire side clay | -5.6    | 1.3    | 2.5           | 5.6           | 11.2               |
| Top side clay  | -0.5    | -0.4   | 1.2           | 1.4           | 1.9                |

### III. Summarized gravity drainage results.



### 9. Clay wire side filler distribution under vacuum drainage.

observed distribution. The variation in the kaolin clay is still larger than that seen with PCC, but the effect is relatively small compared to the wire side.

#### Effects of vacuum drainage

In the second set of experiments, the effects of drainage velocity on filler distribution were investigated. This was done by examining the same four cases again, but using an applied suction of 33.9 kPa to remove the water, and comparing the results with those found using gravity drainage. All other suspension characteristics were kept constant. The first case was the wire side clay; **Fig. 9** shows the results.

Under the effects of vacuum drainage, the general trend of the filler distribution was the same: the knuckle zones contained the least filler material, the threads contained close to the sample mean, the outer opening was above the average,

and the inner opening had the highest concentration (Fig. 9). The noteworthy change is that compared to the gravity drainage case, the maximum variation increased by 46%, from 11.2% to 16.4%. This difference is attributed to the fact that under vacuum drainage conditions, mean drainage velocity is considerably faster than in gravity drainage (0.12 m/s compared to 0.03 m/s), and consequently, the filler mobility is correspondingly higher.

The analysis was repeated on the other three sample types. These results are presented in **Table IV**. Table IV shows that the concentration difference between the inner opening and knuckles on the wire side of the PCC filler samples was 11.5%. Under gravity drainage, this value was found to be 5.2%, which represents an increase in the total variation of about 120%. As noted above, the corresponding increase with clay filler was 45%. It is believed that this dramatic increase in concentration variation found in the PCC filler samples can be explained by the nature of the electrostatic bonds with the pulp fibers. The bonds are susceptible to breakage by large hydrodynamic shear forces [12]. Under gravity drainage, when the shear forces are low, the bonds tend to hold the PCC particles to the wood pulp fibers and resist the distributing effects of the flow field. However, during formation with vacuum drainage, the hydrodynamic shear forces are much higher and more bonds are broken, allowing a larger percentage of PCC particles to move with the flow field.

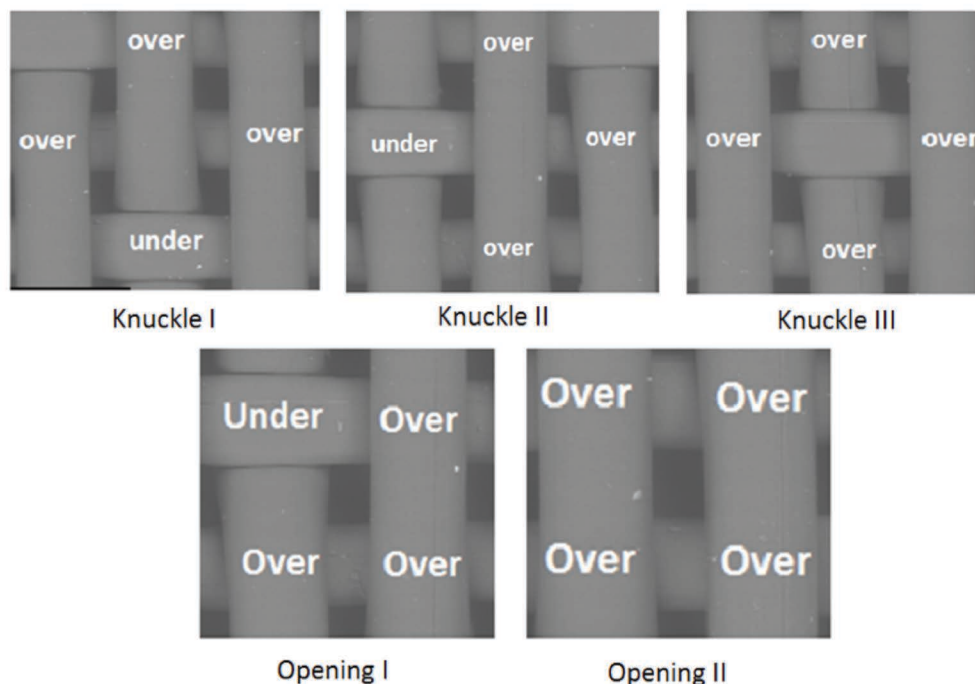
In contrast with the wire-side behavior, with applied vacuum, there was not a statistically significant increase of the maximum variation for the top side samples. We speculate that while the total dewatering rate was significantly higher under vacuum than with gravity drainage, the flow field variations (ratio of maximum to minimum velocity) on the top side are unaffected by the dewatering rate, owing to the intermediary pulp mat. The near independence of top-side flow field variation with applied vacuum would result in a distribution of

| Sample         | Knuckle | Thread | Outer Opening | Inner Opening | Maximum Difference |
|----------------|---------|--------|---------------|---------------|--------------------|
| Wire side PCC  | -6.7    | 1.4    | 4.4           | 4.8           | 11.5               |
| Top side PCC   | -0.8    | 0.2    | 0.5           | 0.7           | 1.5                |
| Wire side Clay | -5.7    | 0.4    | 5.0           | 10.7          | 16.4               |
| Top side clay  | -0.7    | 0.0    | 0.5           | 1.3           | 2.0                |

### IV. Summarized vacuum drainage results.

| Sample              | Knuckle | Thread | Outer Opening | Inner Opening | Maximum Difference |
|---------------------|---------|--------|---------------|---------------|--------------------|
| Wire side - vacuum  | -6.5    | 1.7    | 4.4           | 4.8           | 11.3               |
| Top side - vacuum   | -0.6    | 0.1    | 0.2           | 0.5           | 1.1                |
| Wire side - gravity | -1.5    | 0.1    | 1.5           | 2.8           | 4.3                |

### V. Results of retention aid tests.



10. Different knuckle and opening geometries in AstenJohnson Monoshape fabric.

filler on the top side that is independent of the drainage rate.

## Effect of retention aids

Additional samples were made to test the effects of retention aids on the surface filler distribution of PCC. These samples were formed under vacuum drainage to simulate paper made in industry. A second test was performed, with retention aids and gravity drainage, as a control. As before, all other pulp suspension characteristics remained constant. The wire and top sides of the vacuum samples were analyzed, as were the wire side of the gravity samples. **Table V** shows the results.

Table V shows that, on the wire side of samples made with retention aids in vacuum drainage, the maximum PCC concentration variation was 11.3%. This number may be compared with the 11.5% maximum difference in PCC concentration (Table IV) with no retention aids in vacuum drainage. Because there was no statistically significant difference between these two results, we concluded that the retention aids had no effect on distribution in this case. It is believed that the reason for this result is that the very large hydrodynamic shear forces present during vacuum formation on the wire side of the handsheets disperses the filler flocs formed by the retention aids, causing the filler material to behave as if the retention aids were not present. Under gravity drainage, the maximum PCC concentration variation with retention aids (4.3%) is statistically lower (at the 95% confidence interval) than that without retention aids (5.2%) (Table I). With gravity drainage, the hydrodynamic shear forces are correspondingly smaller

than with vacuum drainage, and therefore, the retention aid is more effective at reducing the mobility of the filler particles.

In a similar manner, the distribution on the top side of the samples was tested. The maximum difference was found to be 1.1% with retention aids present in the suspension, compared to 1.5% without the retention aids. This represents a statistically significant improvement in the uniformity of the filler material when retention aids are used. Once again, this is attributed to the relatively low shear forces present during formation of the top side of the handsheets. Based on these three results, we surmised that retention aids improve the surface distribution of filler only if the shear forces are sufficiently low.

## Experiments with industry forming fabric

Similar analyses of the surface distribution of PCC was carried out on paper samples made with a modern forming fabric (AstenJohnson Monoshape). The goal of this set of experiments was to see if the general distribution trends previously observed hold true with a fabric used in industry. The suspension was prepared in the same manner as for all previous samples, with PCC filler and retention aids. The water was removed by vacuum drainage. In one repeat of the forming fabric, there are two unique opening geometries and three unique knuckle geometries, which can be seen in **Fig. 10**. The elements are categorized by the position of the surrounding cross-machine direction threads. **Table VI** shows the relative filler concentrations in the regions.

| Region      | Normalized Filler Concentration |
|-------------|---------------------------------|
| Opening I   | +2.4%                           |
| Opening II  | +3.4%                           |
| Knuckle I   | -1.7%                           |
| Knuckle II  | -1.8%                           |
| Knuckle III | -2.1%                           |

#### VI. Results of tests with industry forming fabric.

With this finer fabric, the regions of paper formed over the knuckles still contained the least filler material, and the regions formed over the openings contained the most. The maximum difference occurred between what was termed “Opening II” and “Knuckle III,” and was equal to 5.5%. The equivalent difference on the plain weave fabric was 11.3%. The finer fabric showed a lower magnitude of the variation between zones, but a higher spatial frequency.

### CONCLUSIONS

Samples were made in a modified handsheet former to test the small-scale variations in filler material on the surface of paper. Different formation conditions were controlled to investigate the effects on the samples, including filler type, dewatering rate, presence of retention aids, and forming fabric geometry.

The most significant variations in filler concentration were found to result from the placement of wood pulp fibers. The filler tended to be concentrated between fibers, creating distinct pockets on the paper surface. There was a comparatively small, but distinct and repeated variation in the surface filler concentration caused by the forming fabric geometry and corresponding drainage flow field. In all experimental tests, the filler distribution was found to be correlated to the localized variations in flow field velocity. Areas of paper formed in regions of high flow contained more filler material than the paper areas formed in low flow regions. Paper formed over knuckles in the forming fabric contained the least filler material, the threads contained more, and the paper formed over openings in the fabric had the highest filler concentration. In all samples, the distribution of the filler material was more pronounced on the wire side of the samples than the top side; the flow was more uniform on the top side. On the wire side of the paper, increasing the dewatering rate increased the variations in filler concentration. However, on the top side of the paper, an increase in the dewatering rate had minimal effect on the distribution. These findings can be explained by considering the hydrodynamic forcing acting on filler particles; when the forcing is high, such as near the wire side under vacuum drainage, filler mobility is high.

The discrepancies seen in the variations of PCC and kaolin clay filler were attributed to the electrostatic forces between

pulp fibers and filler particles. These attractive forces likely reduced the variation in surface filler concentration by attaching the small particles to the pulp fibers, thereby resisting the distributing effects of the flow field. Consequently, the distribution of PCC filler was more uniform than that of the clay. However, this effect was minimized at higher drainage rates, which produced large hydrodynamic shear forces that broke the electrostatic bonds and allowed a larger percentage of the PCC particles to move freely with the drainage flow. The same effect was observed with retention aids. At lower drainage rates, the bonds formed by retention aids improved the uniformity of the surface filler distribution, but under the effects of vacuum drainage on the wire side, the retention aids showed minimal effect on the filler variation.

Paper made with a finer forming fabric displayed the same general distribution trends as the coarse fabric: the knuckles contained the least filler, and the openings contained the most. Fluctuations in local filler distribution are dependent on the fabric geometry, so paper made with this fabric showed a higher spatial frequency of variation, but a considerably lower magnitude of variation, than the samples made with the coarse fabric. Filler particles are not believed to migrate notably in either the press or dryer sections of a paper machine; consequently, the spatial fluctuations in filler concentration observed here are expected to be present in industrially made paper. **TJ**

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### LITERATURE CITED

- Hagglblom-Ahnger, U., Pakarinen, P., Odell, M., et al., *TAPPI J.* 81(5): 149(1998).
- Odell, M., *Appita J.* 53(5): 371(2000).
- Roux, S., Feugeas, F., Bach, M., et al., *J. Microsc.* 229(1): 44(2008).
- Antoine, C., Mangin, P.J., Valade, J.L., et al., in *Advances in Printing Science and Technology* (J.A. Bristow, Ed.) Vol. 23, John Wiley and Sons, Hoboken, NJ, USA, 1997, pp. 401-414.
- Fordsmand, H., Maloney, T., Kananen, J., et al., “The effect of filler distribution on gravure printability of SC paper,” *TAPPI Int. Print. Graphic Arts Conf.*, TAPPI PRESS, Atlanta, GA, USA, 2006, p. 1.
- Szikla, Z. and Paulapuro, H., *Pap. Puu* 68(9): 654(1986).
- Radvan, B., in *Handbook of Paper Science*, Elsevier Scientific Publishing, Amsterdam, The Netherlands, 1982, Chap. 4.
- Tanka, H., *Tappi* 65(4): 95(1982).
- Alince, B. and Bednar, F., *J. Appl. Polym. Sci.* 88(10): 2409(2003).
- Eklund, D. and Lindstrom, T., *Paper Chemistry: An Introduction*, D.T. Paper Science Publications, Turku, Finland, 1991.
- Ven, T.V.D., *J. Pulp Pap. Sci.* 10(3): 57(1984).
- Shin, J-H., Han, S.H., Sohn, C., et al., *TAPPI J.* 80(11): 179(1997).
- Peng, H. and Green, S.I., *Nord. Pulp Pap. Res. J.* 27(4): 783(2012).

14. Vakil, A., Green, S.I., and Olyaei, A., *Nord. Pulp Pap. Res. J.* 24(3): 342(2009).
15. Montgomery, J., Green, S.I., Vanerek, A., et al., *J. Pulp Pap. Sci.* 36(3): 162(2010).
16. Montgomery, J., Green, S.I., and Vanerek, A., *Nord. Pulp Pap. Res. J.* 25(4): 463(2010).
17. Modgi, S., McQuaid, M., and Englezos, P., *Pulp Pap. Can.* 107(5): 48(2006).
18. Ormerod, D., Simon, G., and Gibbon, D., *Tappi J.* 71(4): 211(1988).
19. Gibbon, D., Simon, G., and Cornelius, R., *Tappi J.* 72(10): 87(1989).
20. Goldstein, J., *Scanning Electron Microscopy and X-ray Microanalysis*, Kluwer Academic/Plenum Publishers, New York, 2003.
21. Goodhew, P.J., Humphreys, F.J., and Beanland, R., *Electron Microscopy and Analysis*, Taylor and Francis, New York, 2001.
22. Russ, J., *Fundamentals of Energy Dispersive X-ray Analysis*, Butterworths & Co. Ltd., Toronto, ON, Canada, 1984.
23. Green, S.I., Wang, Z., Waung, T., et al., *Comput. Fluids* 37(9): 1146(2008).
24. Herzig, R. and Johnson, D.B., *TAPPI J.* 82(1): 226(1999).
25. Danby, R., *TAPPI J.* 1(9): 3(2002).
26. Olyaei, A., "Simulating the formation of a fiber mat," M.S. thesis, University of British Columbia, Vancouver, BC, Canada, 2012.

## ABOUT THE AUTHORS

We chose this topic to research because we wanted to determine whether hydrodynamic watermarks in paper are in part the result of the spatial variation in filler distribution in the sheet.

In prior work, we proved that the forming fabric structure, at the level of the individual filaments of the fabric, produces flow field spatial variation along the fabric surface. In this research, we wanted to establish whether this flow field variation affects the distribution of filler material in the sheet.

Filler location in a paper sheet is most strongly correlated with the location of wood fibers, which are almost randomly dispersed in the sheet. The filler concentration variation attributable to fabric structure is just a fraction of that resulting from wood fiber positional variability. Therefore, the detection of the small "signal" caused by fabric structure in the large "noise" from fiber effects required the use of averaging over many fabric weave repeats, which in turn required one to consistently find the position of the fabric weave repeats in a dried handsheet.

It was surprising how deep into the paper structure (even as far as the surface of the handsheet opposite to the fabric) the hydrodynamic variation of filler distribution could be observed.

This is the first paper to show that the forming fab-

ric structure affects filler distribution, which presumably affects printability. Forming fabric manufacturers can benefit from this information as it is another factor to be considered in fabric design.

Several next steps are possible. One would be to systematically explore the role of dewatering rate on filler distribution in the sheet. A second step would be to study the role of retention aid type and concentration on filler distribution at the fabric-filament level. Yet a third would be to study the effect of forming fabric geometry on filler distribution.

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