Application of foamed additives to the surface of wet handsheets

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ABSTRACT: We explored the application of foamed wet-end additives onto wet handsheets to qualify our method of application and to demonstrate the method's usefulness for prescreening additives and foaming agents for packaging applications.

We modified a laboratory drawdown coating machine to allow coating of wet handsheets with foamed additives. Initial sheet solids were adjusted to a target of 8%–25% by vacuum. Foam layer thickness was set mechanically. After application, the foamed additives were drawn into the sheet with vacuum. The additive dosage was adjusted by altering its concentration within the foaming formulation. We evaluated more than 100 foaming agents and 10 strength additives, comparing wet-end and foam-assisted addition with no addition on recycled linerboard and virgin linerboard furnish. Foam-assisted addition typically displayed a much steeper dose-response curve and much higher maximum strength levels than wet-end addition.

Our results suggest potential target applications for this technology, such as lightweighting, and improved strength performance in mills with relatively closed water systems, where strength aids added into the wet end are adversely influenced by accumulation of inorganic ions and organic species.

Application: Wet-end additives can be applied onto the wet sheet via foam-assisted additive application. This keeps the white water cleaner and applies additives in a more concentrated form, resulting in higher chemical efficiency and less interference with other wet-end species. This paper describes a novel device for applying foamed additives to wet handsheets in the laboratory.

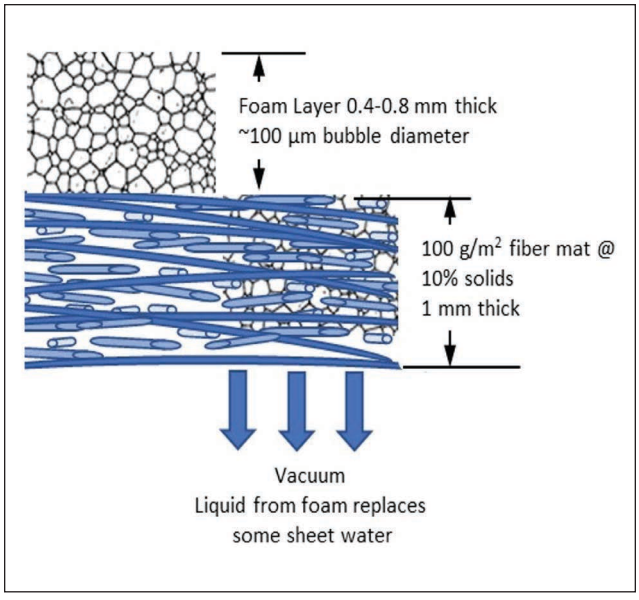
Traditionally, wet-end additives have been added either to the thick stock or to the thin stock (before or after the fan pump). These addition points can be simulated during handsheet studies; however, retention of additives is always less than 100%. Cationic additives may find their way to suitable anionic sites on the fibers or they may combine with non-fiber anionic materials in the wet end [1].

Multiple investigators have experimented with the application of foam (alone or with functional additives) to wet paper or textile substrates [2-4]. The technology is well known in the fabric finishing industry, where increased fabric dryness and effective washing with less water after vacuum dewatering and/or pressing are reported [3-5]. Even though the foam addition step adds a significant amount of water, the higher viscosity of the foam makes the pressure differential created by vacuum application or pressing more effective, resulting in less water left in the sheet.

Kinnunen-Raudaskoski discussed the addition of wet-end additives (especially strength additives) to wet paper on the former via foam [6]. Additives applied to the wet sheet at 10% sheet solids and 100 g/m² wet coating weight are about 10–20 times more concentrated than when applied in the wet end, depending on the headbox consistency, which may be beneficial for additive retention and efficiency. The referenced publication shows results from continuous or dynamic applications (i.e., a pilot or production paper machine), as do all the other foam addition references listed. Access to pilot or production paper machines, the supporting ancillary equipment (foam generator, foam distributor, and dosing systems), and operating expertise is not always available; thus, handsheet studies are a good alternative for comparing the potential of foam-assisted (FA) vs. wet-end (WE) addition for evaluating the effectiveness of available strength additives on furnishes of interest and for studying the effects of water chemistry. We are aware that a few research groups have developed techniques to apply foamed additives to wet handsheets, but we have been unable to find any publications where the devices or techniques are detailed.

Additives can also be applied to wet sheets via spray nozzles [7]. Achieving an even application on a handsheet or in a commercial production line with spray nozzles is challenging, and in both cases, nozzle dimensions may limit the particle size or viscosity of the product to be applied. Spray bars are often used in mills, especially for applying starch, and may require some housekeeping due to accumulation of overspray or aerosol material that settles on surfaces [8]. Foamed application of additives may be a viable alternative to spray application.

Application of foam to wet handsheets is also challenging. **Figure 1** shows the general concept and typical conditions for applying foam onto wet handsheets. The foam layer is very thin, typically 0.4 to 0.8 mm, to avoid adding



1. General conditions and approximate dimensions for foam coating of wet sheets.

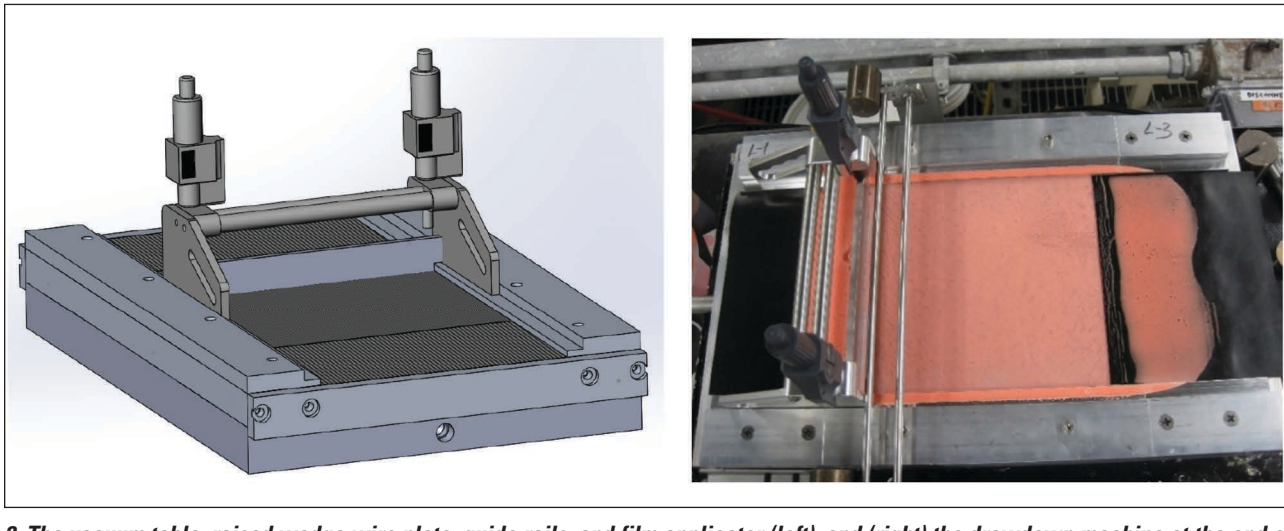
excess liquid mass to the sheet and to ensure that the foam is mostly held within the formed sheet after vacuum application.

We added dye to the foam in some cases to confirm the evenness of the application in the machine direction (MD) and cross direction (CD) and to look at foam penetration depth (z direction of the sheet). As shown in Fig. 1, the foam may penetrate most or all the way through the sheet under the influences of the high vacuum boxes. Keeping the foamed liquid within the wet sheet during vacuum application could help avoid foam in the vacuum box and limit recirculation of liquids that could foam easily in the wet end. The MD, CD, and z-direction distribution of foamed additives will be discussed in more detail in a future paper.

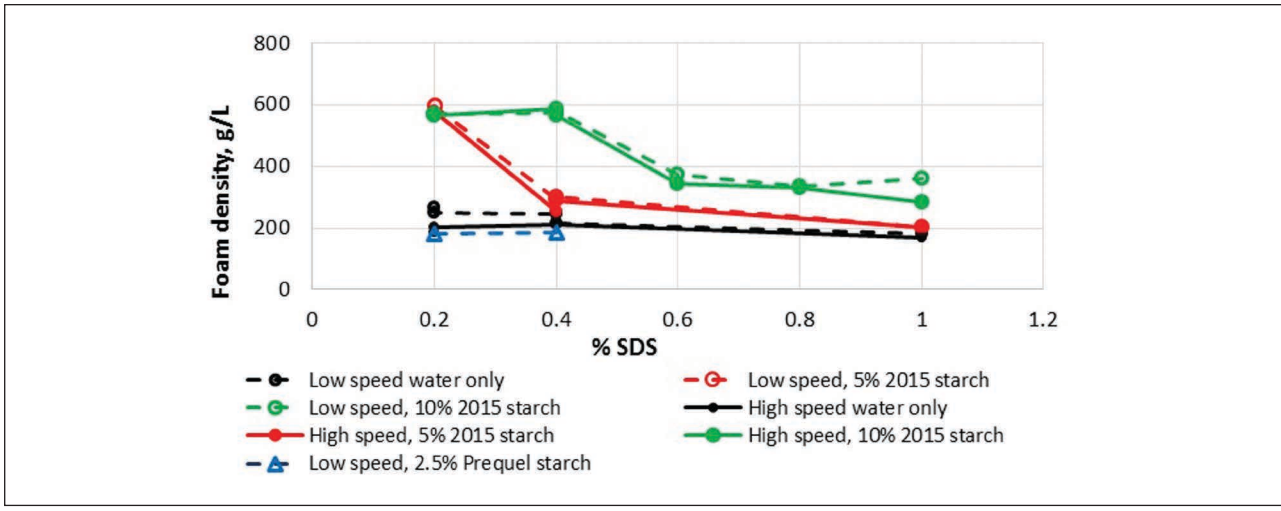
DEVELOPMENT OF AN EXPERIMENTAL FOAM APPLICATION DEVICE AND METHOD

We used a Noble & Wood handsheet machine with a stock proportioner to produce nominal 20 cm x 20 cm handsheets (similar Formax handsheet machines are available from Adirondack Machine, Hudson Falls, NY, USA). Unless otherwise noted, handsheets were targeted at 100 g/m² ovendry (o.d.) and had a forming consistency of about 0.05%. After formation, the handsheets were pressed from 8%–10% to 45%–47% solids between two felts with a Formax roll press (Adirondack Machine) while the sheet was still on the forming fabric. Pressing conditions were 413 kPa gauge pressure at a feed rate of 2.6 m/min (50% of maximum for this press) in all cases. The pressed handsheets were dried against a hot steel drum backed by a drying felt on a Formax drum dryer (Adirondack Machine).

We constructed a wet handsheet coating apparatus by modifying an existing Gardco Model DP-8201 automated drawdown type coater (Paul N. Gardner Co.; Pompano Beach, FL, USA). We fitted the drawdown machine with a vacuum table available from the same source. The holes in the commercial vacuum table were spaced about 25 mm apart, so we added a custom-built wedge wire table with a bar width of 0.80 mm over the commercial vacuum table, thereby reducing the maximum water flow path to 0.40 mm to achieve more even dewatering. Machined aluminum rails were added to provide a track for an Xtra-Value Digital Micrometer II Film Applicator with a heavy drawdown blade (Paul N. Gardner Co.). The applicator was fitted with a digital micrometer on each end of the blade to allow its height to be adjusted precisely (+/- 0.001 mm). Removable sections of the two aluminum applicator rails were used to hold down the edge of the forming fabric and the wet handsheet. The wet handsheet foam coating drawdown machine is shown in **Fig. 2**.



2. The vacuum table, raised wedge wire plate, guide rails, and film applicator (left), and (right) the drawdown machine at the end of a foam application (dye added to improve visibility and show the evenness of the application).



3. The impact of functional additive on the minimum required foaming agent dose vs. foam density (SDS = sodium dodecyl sulfate).

The 100-mesh stainless steel forming fabrics we normally use did not remain in-plane well after a few uses, so we used 80-mesh 43% open area polyester forming fabrics (Component Supply Company; Sparta, TN, USA). This fabric was flexible enough to be held flat by the weight of a wet handsheet.

The clearance between the blade and the wet handsheet surface was set using multiple stacks of two plastic shims of about 1 cm x 4 cm (in the direction of blade travel) by 0.204-mm thick, which were carefully laid on the wet handsheet surface at multiple positions across its width. The blade was adjusted until its movement just barely caused the upper shims to slide on the lower shims. Further adjustment to any height setpoint was made with the integral digital micrometers.

We used a handheld Biohomogenizer MW140 with a 2.5-cm diameter 12-bladed rotor and stator (Biospec Products; Bartlesville, OK, USA) for 60 s to produce 25 g batches of foam. Typically, ~4.5 g of foam were applied to each handsheet at normal application rates. The 25-g batches of foam ensured that a large excess of foam was available for even foam distribution.

The vacuum table under the handsheet mounting area was connected to a vacuum separator and a vacuum pump. We could not effectively seal against the wedge wire surface, so a very oversized vacuum pump was used. The open areas of the wedge wire plate beyond the ends of the handsheets were roughly sealed with pieces of soft neoprene gasket material that overlapped the leading and trailing edges of the handsheets, as shown in Fig. 2. The soft neoprene gasket material served as a foam reservoir at the upstream end and as a collection area for the excess foam on the downstream end of each foam application run. The original crossbar mechanism, normally used for drawing a contacting coating rod across a dry sheet during normal drawdown runs, was used to push the non-contacting film applicator along the applicator rails.

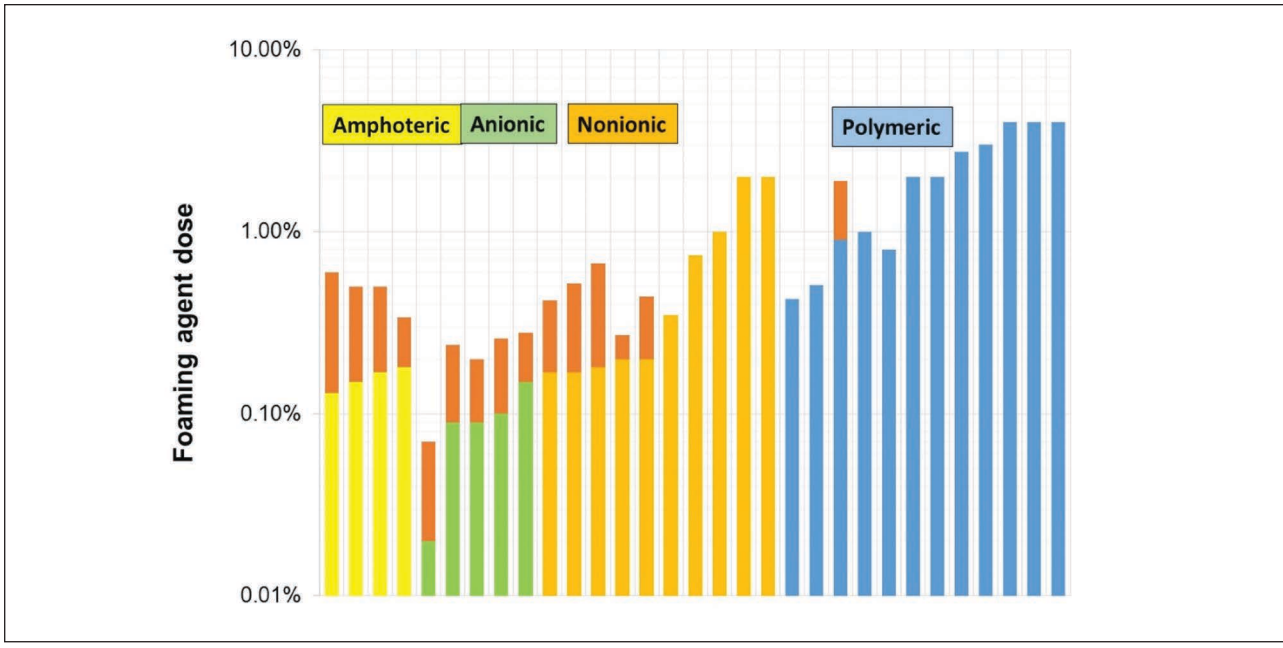
RESULTS

Major foam characteristics and additive application variables evaluated in this study and the results of the testing are discussed below.

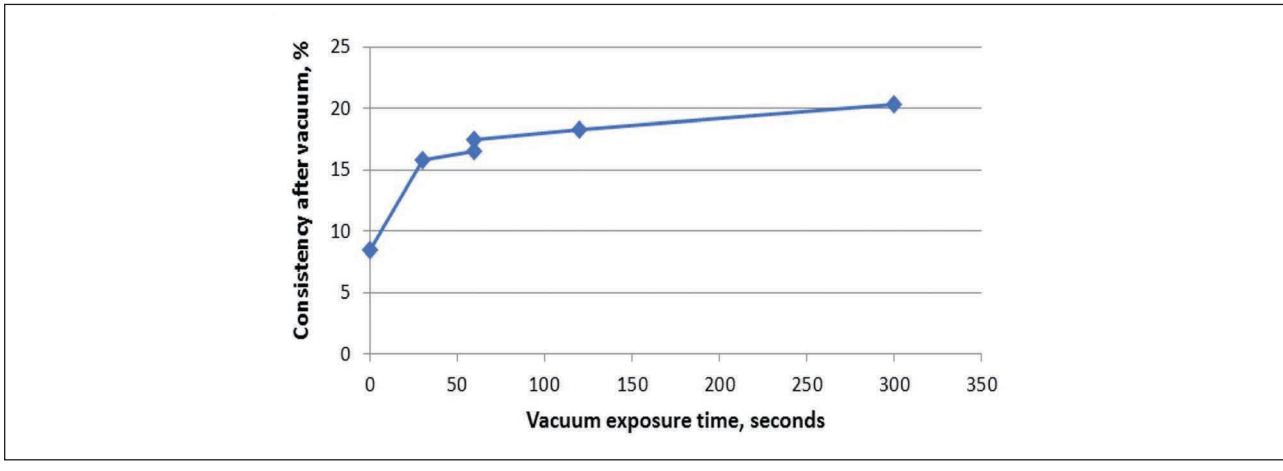
Foam composition and density

Foam composition was set by adjusting the concentration of the foaming agent and the functional additive in the foaming formulation before mixing in the air. We minimized the amount of foaming agent used to reduce its impact on bonding [9,10]. **Figure 3** shows the impact of foaming agent dose on foam density after 60 s of homogenization when the amount and type of starch were varied, using sodium dodecyl sulfate (SDS) as a foaming agent, for two rotor speeds. The SDS dose required to foam water with no additives was less than 0.2 wt% on liquid to reach 200 g/L foam density; increasing the SDS dose did not change the foam density significantly. Foam density was limited to 200 g/L or higher when produced with our handheld homogenizer, because the foam must remain fluid enough to fall back into the rotor via gravity in the 200 mL mixing beaker used in this study.

When 2.5 wt% of Prequel 500 wet-end starch (Solenis LLC; Wilmington, DE, USA) was foamed with SDS, the foam density was 200 g/L foam density, regardless of the foaming agent concentration. When 5% of Ethylex 2015 surface treatment starch (Tate and Lyle; Decatur, IL, USA) was foamed with SDS, the minimum SDS concentration sufficient to produce 250 g/L foam density was 0.4 wt% on liquid mass, at low and high rotor speed. When 10% Ethylex 2015 starch was foamed with SDS, the minimum dose of SDS needed to produce 300–350 g/L foam density was 0.6 wt% on liquid mass, an impractical SDS dose. As before, little or no impact of homogenizer rotor speed was observed. This clearly shows that the minimum dose of foaming agent is significantly impacted by the type and amount of functional additive present.



4. Minimum effective dose of various foaming agents needed to produce 300 g/L (lower bar) and 200 g/L (dark orange upper bar) foam density. The color of the lower bar identifies the type of foaming agent. Some foaming agents could not reach 200 g/L foam density at any dose.

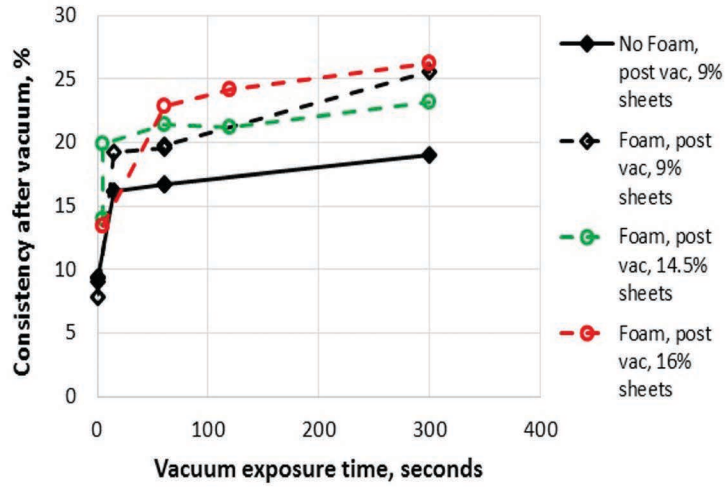


5. Sheet consistency after exposure to vacuum (-26 kPa) for various time intervals.

Even though SDS is known to be a low cost and effective foaming agent, it is not a good choice for foamed additive applications because of its significant impact on bond strength. Figure 3 is presented only to show the interaction between the functional additives and the minimum required foaming agent dose.

After we determined the minimum effective dose of foaming agent for more than 100 foaming agents in deionized (DI) water only, we completed a more detailed evaluation of the best 30 foaming agents with varied doses of a range of dry strength additives. **Figure 4** shows the foaming agent dose required to generate foam at various densities for water only. Some foaming agents cannot reach 200 g/L foam density, regardless of dose, and others can reach this foam density range only with impractically high doses. The best foaming agents were typically nonionic, anionic or amphoteric.

As shown in Figs. 3 and 4, foam density varied over a relatively small range of about 200–300 g/L when we used a non-pressurized handheld homogenizer to generate foam. We targeted 250 g/L foam density for the rest of this study, because varying the foam density within the available range was neither practical nor instructional. We are aware that pressurized rotor-stator type foam generators can produce foam with density as low as 100 g/L [6]. We will explore the role of foam density more fully when we have the capability to vary foam density over a wider range. The data presented here is intended to show only a trend of interaction between required minimum effective foaming agent dose, functional additive type, and dose of the functional additive.



6. Effect of initial sheet solids, foam application, and post-foam vacuum exposure time on consistency after vacuum.

Handsheet consistency before and after foam application

The impact of handsheet consistency prior to foam application was explored by controlled application of vacuum to the formed handsheet before applying foam. As shown in **Fig. 5**, handsheet consistency was controlled well by varying the length of time the sheet was exposed to low levels of vacuum. In this case, the furnish was 100% bleached softwood (SW), refined to 400 mL CSF and formed into 100 g/m² handsheets. Changing handsheet parameters such as fiber type, basis weight, or freeness would likely alter the consistency vs. vacuum exposure time response.

We added foam to the handsheets, then vacuumed the foam into the sheet, and then pressed and dried as usual. The untreated sheets were vacuumed under the same conditions as the sheets with foam applied. Measured vacuum was typically higher for the foam-treated sheets, at least until the air breakthrough point.

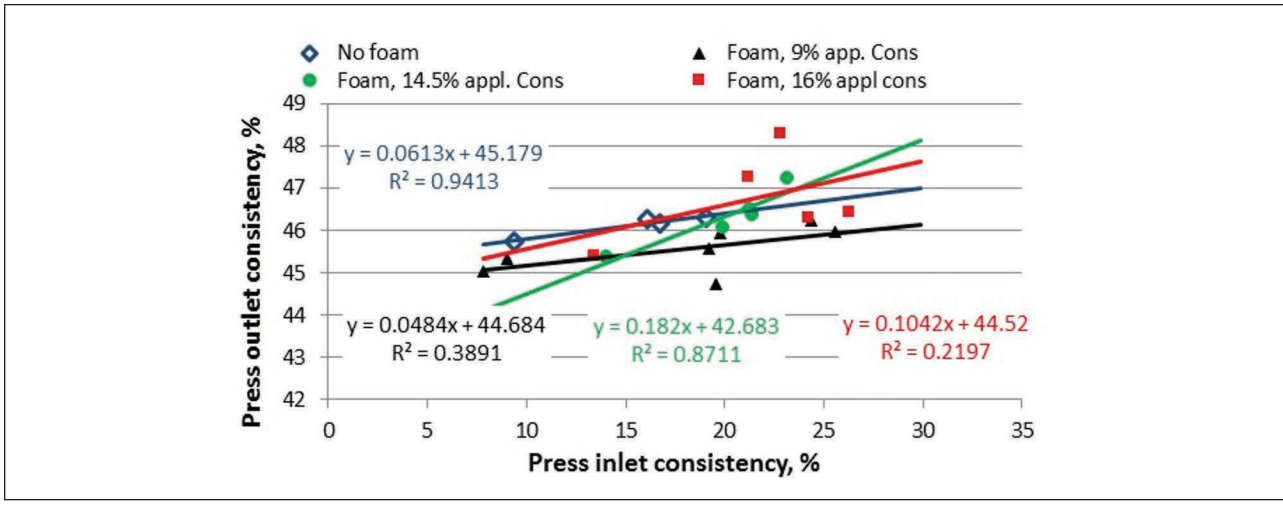
Addition of foam before the final vacuum treatment raised the final sheet consistency by 4%–6%. Raising the sheet consistency prior to foam application also raised sheet consistency after the final vacuum treatment by 2%–4%, as shown in **Fig. 6**. The effect of post-foam vacuum application time was also clear. This confirms the work of Skelton [2] and extends it to show the impact of pre-foam sheet consistency and post-foam vacuum treatment.

Handsheet consistency after pressing

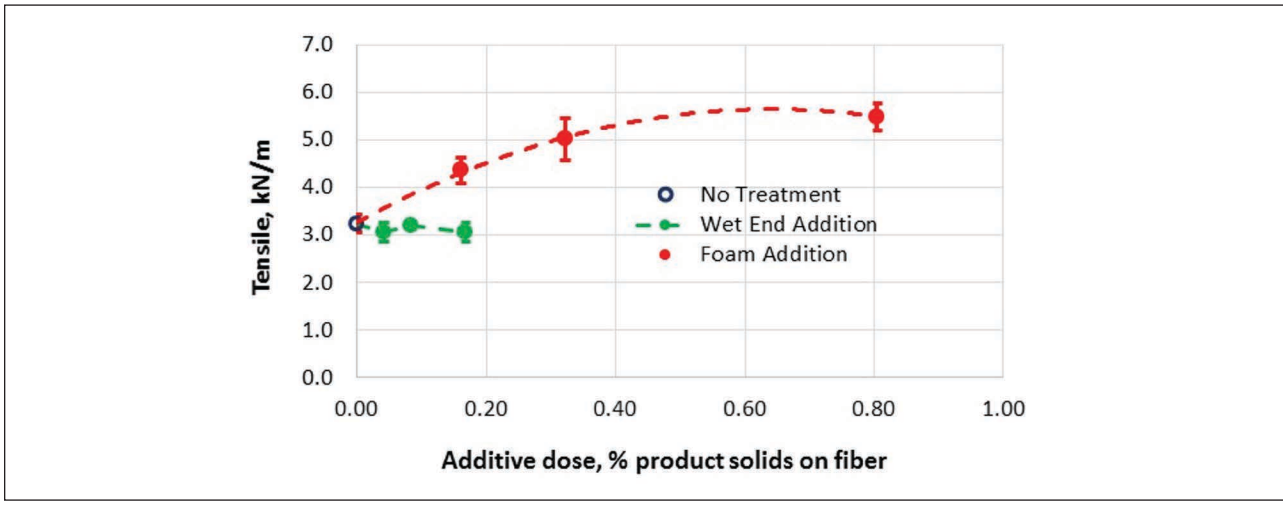
The elevated consistency due to the foam treatment and vacuum exposure persists to some extent through pressing, as shown in **Fig. 7**, which indicates that higher press inlet consistency slightly increases press outlet consistency. The foam treated sheets have higher solids after vacuuming (Fig. 6), but this effect cannot be clearly distinguished after pressing (Fig. 7). This may be because the very low speed lab press tends to operate in pressure-limited mode. With such a narrow range of press discharge consistency, a substantial amount of data would be required to show a small effect. Characteristics of flow-limited and pressure-limited press nips are explained in more detail by Paulapuro [11].

Strength testing details

The influence of FA addition of dry strength additives on handsheet strength properties was the main focus of this work. Over a period of more than 18 months, handsheets were produced under more than 1000 conditions using a wide range of furnishes, strength additives, and foaming agents. The WE addition was simulated by dosing the stock aliquot drawn from the Noble & Wood proportioner for each individual handsheet made (simulating thin stock addition). Unless otherwise noted, handsheets were 100 g/m². Foam at ~250 g/L density was applied to as formed handsheets (~9% solids), and the handsheets were vacuumed to 20% solids before pressing. The control handsheets (no foam or wet-end addition) were also vacuumed at the same conditions. The foam layer was nominally 0.41 mm thick (~110 g/m² wet foam added); dry foam weight was up to 1% of dry sheet weight, depending on the additive dose. Pressing typically resulted in 45%–47% solids. Drying was at 113°C until dry. Individual handsheets were weighed after conditioning, and strength values for the individual handsheets were corrected to 100 g/m² o.d. All paper testing after conditioning utilized normal handsheet testing methods: TAPPI Standard Test Methods T 494 om-13 "Tensile properties of paper and paperboard (using constant rate of elongation apparatus)"; T 403 om-15 "Bursting strength of paper"; and T 822 om-16 "Ring crush of paperboard (rigid support method)". Wet tensile properties were determined after a 2-h soak in 20°C deionized water, followed by blotting, and then testing per T 494 om-13.



7. Impact of handsheet consistency and foam application on handsheet consistency after pressing.



8. Dose-response curves for wet-end (WE) and foam-assisted (FA) addition for 100% virgin linerboard for a structured polyacrylamide (PAM) dry strength additive. Error bars are 1 standard deviation (SD).

Strength additive dose

Virgin linerboard (VLB) is typically produced from mostly unbleached kraft softwood fibers. These fibers are strong; sheet failures tend to result from bond failures rather than from fiber failures. Increasing the bonded area can dramatically improve sheet strength. This can be achieved by refining, at the cost of refining energy, drainage, drying rate and machine speed. Improved bonding via dry strength additives can maintain drainage and machine speed. High conductivity and particularly dissolved organic material can interfere with the effectiveness of wet-end addition of dry strength additives. This makes it particularly difficult to use dry strength additives effectively in the wet end of virgin linerboard mills if the brown stock washing is less than ideal.

We obtained a bucket of stock from a Southern U.S. virgin linerboard mill machine chest at 2% consistency, to retain the chemical environment from the wet end at the mill. Freeness was ~750 CSF; the stock was diluted from 2% to handsheet-forming consistency with tap water.

Figure 8 compares the tensile strength response for WE and FA addition of a structured polyacrylamide (PAM) dry strength additive. No significant dose response was observed for WE addition, but FA addition showed a very strong tensile strength dose response, up to 70% improvement over no treatment or WE addition.

We generated comparable data for other strength properties. A compact way to display such data is in a color gradation chart, which can be constructed using the conditional formatting command to format the cell background colors in some spreadsheet programs. **Table I** contains values for the percent increase over the control (untreated) value (e.g., 100% increase means the strength value doubled). A significant negative value indicates a detrimental dose response. Each strength property column is conditionally formatted such that the best (highest in this case) values are shades of green, the worst values are shades of red, and the mid values are shades of yellow. This allows very fast visual assessment of each row and column of data. The FA

	Dry Tensile	Wet Tensile	Wet/ Dry	Dry Stretch	Wet Stretch	Dry TEA	Wet TEA	Mullen	Ring Crush	Water Drop	Porosity
WE 0.042%	-6%	-14%	-9%	-7%	-4%	-14%	-21%	-11%	-4%	26%	-20%
WE 0.084%	-1%	-13%	-12%	2%	4%	-1%	-15%	13%	-6%	-12%	-19%
WE 0.168%	-6%	-14%	-9%	-3%	5%	-11%	-15%	3%	-3%	-2%	-16%
FA 0.161%	35%	150%	85%	36%	101%	70%	336%	78%	22%	332%	-31%
FA 0.322%	55%	213%	102%	44%	104%	113%	468%	136%	34%	332%	-19%
FA 0.805%	70%	280%	124%	51%	116%	135%	598%	151%	39%	234%	-15%
Average SD, as %	5.9%	7.9%		7.7%	7.2%	11.7%	15.7%	7.4%	7.2%	17.2%	20.3%

WE = wet-end; FA = foam-assisted; SD = standard deviation; TEA = tensile energy absoprtion.

I. Color gradation chart for virgin linerboard (VLB) treated with structured polyacrylamide (PAM). Colors within a column (for each individual strength property) provide a visual indication of the effect. Values shown are percent over the control (untreated) value. Average SD is the average of the SD of each condition's values divided by the condition's value.

addition rows are shades of green for all strength properties reported, indicating at a glance a strong strength response for FA addition. The WE addition rows are shades of yellow or red, indicating no change or declines of strength responses for WE addition for all strength properties reported.

Within the FA addition rows, a positive dose response (a trend from lighter green toward bright green) is observed as strength additive dose increases, for all properties reported. The WE and FA addition can be compared at nearly the same dose in the third and fourth row of Table I. The differences in the responses for the various properties of interest are easy to see.

We will continue to use this method of data display, to allow large amounts of data to be presented in a limited number of tables. We added an extra row at the bottom of the table to display the average standard deviation value (from the four reported percent increases and the two untreated values not shown), a sort of grand average standard deviation for that strength property, as an indication of the robustness of the data.

Fiber furnish and water variables

Recycled linerboard (RLB) is produced from recycled corrugated containers, which include some first time and some many times recycled fibers. The fiber usually contains some VLB, virgin corrugating medium (NSSC), recycled containers, mixed papers, and minor amounts of mechanical fiber and filler. Recycled linerboard usually contains dissolved lignin, starch, many other papermaking chemicals, and dissolved salts. Recycled linerboard sheets may fail from a combination of fiber failure and bond failure and are known to respond reasonably well to some dry strength products, although the magnitude of the response may be influenced by the conductivity and the dissolved organics content.

Our RLB was received as an edge roll; its measured freeness upon repulping was 370 CSF. We compared strength increase results from WE and FA addition over the control (untreated) handsheets for handsheets diluted and formed with relatively clean water and those from handsheets diluted and formed with relatively dirty water. The clean handsheet formation water was tap water; its conductivity was 480 µS, and its pH was 7.3. The dirty handsheet formation water was tap water with sodium sulfate added to raise the conductivity to 2100 µS, and 0.9 wt% of fiber of Indulin C soluble lignin (Ingevity; North Charleston, SC, USA) was added to simulate extensive wet-end water recirculation in a mill environment. The dirty formation water pH was 7.0. The dry strength additive was a structured PAM.

The results of those runs are shown in **Table II** in the form of a color gradation chart, with a row at the bottom displaying the average standard deviation for each strength property. The bonding properties were significantly better when the dilution water was clean for the WE addition. The FA addition results were about the same whether the forming water was dirty or clean, and results were significantly better than the WE addition results for the clean and dirty forming water, even though the dose of dry strength additive was 24% lower for the FA addition handsheets. FA addition was less sensitive to water conditions than WE addition and produced a higher strength response, even at a lower dose than WE addition for this application.

Handsheet basis weight (lightweighting potential)

Lightweighting (reduction of sheet basis weight while maintaining critical strength properties) is a high interest topic in the packaging industry. Successful lightweighting can result in substantial fiber cost savings and paper machine speed increases, with substantial savings potential.

	Dry Tensile	Wet Tensile	Wet/ Dry	Dry Stretch, %	Wet Stretch, %	Dry TEA	Wet TEA
0.21% WE, clean	9%	31%	31%	11%	2%	30%	34%
0.16% FA, clean	24%	116%	116%	27%	85%	65%	318%
0.21% WE, dirty	5%	17%	12%	-6%	-6%	2%	17%
0.16% FA, dirty	25%	129%	83%	24%	112%	46%	374%
Average SD, as %	6.8%	28.0%		11.5%	11.4%	18.3%	16.6%

WE = wet-end; FA = foam-assisted; SD = standard deviation; TEA = tensile energy absoprtion.

II. Color gradation chart for 100 g/m² recycled linerboard (RLB) handsheets diluted and formed with addition of clean vs. dirty water, for a structured PAM, for wet-end (WE) and foam-assisted (FA) addition. Values shown are percent over the control (untreated) value. Average SD is the average of the SD of each condition's values divided by the condition's value.

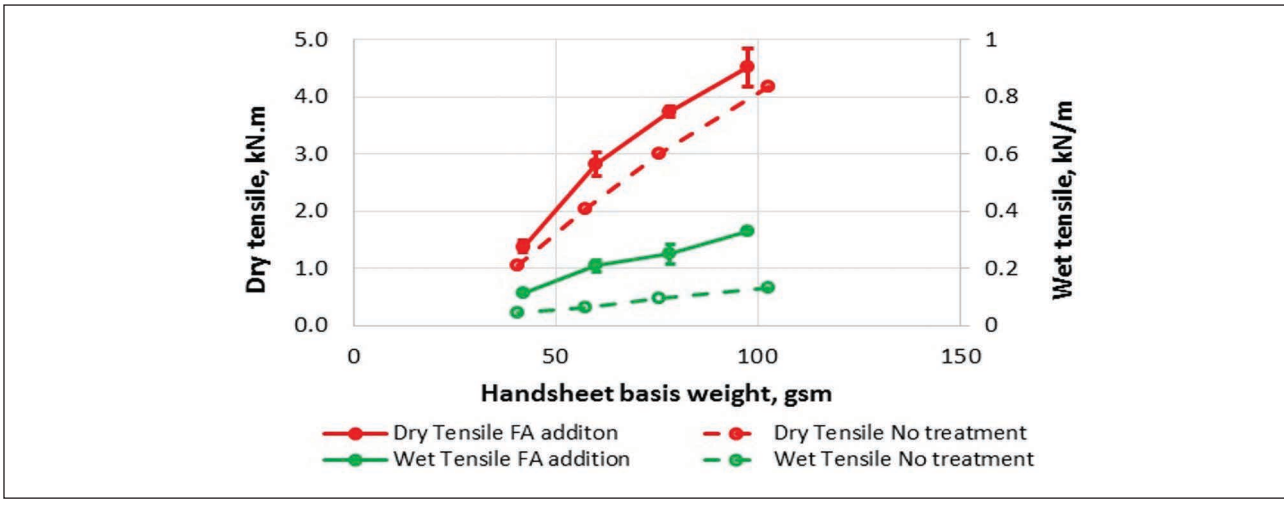
We ran a series of FA addition experiments on RLB furnish to determine if FA addition could facilitate lightweighting. As the handsheet basis weight decreased, we decreased the additive dose proportionately by reducing the concentration of the additive in the foam while maintaining the coating layer thickness at 0.41 mm. When the handsheet basis weight was very low, some of the foamed additive may have been drawn completely through the handsheet by the vacuum. A basis weight reduction of 3%–10% with properties maintained would be considered a huge success in most mills. A wide basis weight range (40–100 g/m²) was tested to allow enough data points and range of strength values to show resolution within the limitations of the handsheet FA addition method.

Figure 9 shows the wet and dry tensile strength of handsheets with 0.4 wt% of a structured PAM and handsheets with no dry strength additive. The strong response of dry and wet tensile strength to sheet basis weight was as expected. The resolution of the method is sufficient to show that basis weight reductions of as much as 15% may be feasible with FA addition of structured PAM in the range of 100 g/m² basis weight, while maintaining dry tensile properties. The FA addition can be used at sheet weights of 150 g/m² or more if the sheet is relatively permeable.

Figure 9 also shows that the FA addition shifted the wet tensile values into a much higher range, compared with the untreated handsheet values. This suggests that such a treatment may allow the mill to produce an entirely new grade with the same furnish.

Dry strength additive screening

We evaluated eight synthetic dry strength additives at a



9. Lightweighting simulation on recycled linerboard (RLB) furnish, with no treatment and 0.4 wt% of a structured PAM added by FA addition. Error bars are 1 standard deviation.

	Dry Tensile	Wet Tensile	Wet/ Dry	Dry Stretch	Wet Stretch	Dry TEA	Wet TEA	Porosity	Water Drop
Structured PAM 1	16%	68%	45%	9%	34%	28%	129%	-12%	25%
Structured PAM 2	16%	132%	99%	15%	108%	35%	408%	-3%	89%
PVAm 1	26%	420%	311%	17%	169%	45%	1154%	2%	426%
PVAm 2	16%	282%	230%	8%	165%	27%	873%	-17%	134%
PVAm 3	29%	404%	292%	29%	193%	60%	1198%	8%	385%
GPAM 1	19%	97%	66%	21%	61%	37%	196%	-7%	-38%
GPAM 2	31%	261%	176%	36%	183%	71%	896%	-3%	-21%
Amphoteric PAM 1	24%	33%	8%	33%	17%	56%	48%	-11%	-29%
Average SD, as %	11.3%	7.8%		11.4%	13.0%	15.4%	22.0%	7.2%	12.0%

PAM = polyacrylamide; PVAm = polyvinylamines; GPAM = gloxalated polyacrylamides; SD = standard deviation; TEA = tensile energy absoprtion.

III. Dry strength additive screening results. Values shown are percent over the control (untreated) value. Average SD is average of the SD of each condition's values divided by the condition's value.

single dose each for tensile properties, expressed as percent increase over the control (no treatment) values. Most strength aids display a dose-response curve that reaches a maximum response; addition beyond that dose produces no further strength benefit. The maximum effective dose was used in all cases, to produce a first pass indication of the potential from each product for the evaluated furnish and other conditions. This process can be used to eliminate products that do not warrant further testing at those conditions. The dry strength additives evaluated included two structured polyacrylamides (structured PAM), three polyvinylamines (PVAm), two gloxalated polyacrylamides (GPAM), and an amphoteric polyacrylamide (APAM). All were commercial products from Solenis LLC.

Results for various tensile properties are presented as color gradation chart in **Table III**. The furnish was RLB at 370 mL CSF, and all dilutions were made with our standard water (DI) water with salt added to mimic tap water in Wilmington, DE, USA. A row has been added to the chart to display the average standard deviation for each strength property as an indication of the robustness of the data.

All the dry strength additives evaluated showed a substantial positive response for every tensile property. The various categories of dry strength additives showed different responses. Very broadly, PVAm > GPAM > APAM > structured PAM for the application conditions tested here. Only one or two examples of most classes of additives were evaluated. When multiple products within a category were evaluated (for example PVAm), significantly different product specific responses were observed. As before, very significant improvements in the wet tensile properties over the no treatment samples were observed for all evaluated products. The actual wet tensile property values were still low enough to avoid repulping issues. These results were consistent with the previous results presented.

DISCUSSION

The modified drawdown coating machine worked well after multiple modifications to ensure the sheet remains flat and in plane during the FA application step. While testing the impact of sheet percent solids at the time the foam was applied, we removed the sheet and weighed it after each vacuuming step to determine the exact moisture content. This was time consuming, but it yielded useful information. We learned that if we applied foamed additives only to as-formed handsheets and held handsheet basis weight constant, the wet sheet thickness was sufficiently consistent to allow us to avoid resetting the clearance over each handsheet. These steps greatly reduced the time required per handsheet, allowing us to concentrate on strength additives as the primary variable. Some areas of investigation, for example, the lightweighting exploratory work, required the more tedious intermediate steps, since the point of that study was to vary the sheet basis weight, which varied wet sheet thickness.

Our work with combinations of foaming agents and several starch types and concentrations has shown that the minimum effective dose of foaming agent is dependent on the type and amount of strength additive. We continued testing every dry strength additive combination and dose to determine the minimum effective foaming agent for that additive and dose to ensure that we did not add more foaming agent than necessary.

We compared WE addition to FA addition in several cases. Many dry strength additives are known to encourage floc formation in wet-end applications, which can result in decreased formation and even some strength loss if strength is not recovered by the improved bonding resulting from the dry strength additive [12]. Floc formation also typically increases drainage, which sometimes allows the machine speed to be increased or the headbox consistency to be lowered. FA addition occurs after the sheet is set, so it cannot impact formation.

In cases where large amounts of dissolved solids are present (especially dissolved organics), dry strength additives tend to be less effective—as we saw in this study. The FA addition does not seem to be impacted by dissolved materials or at least not as much.

We demonstrated that FA addition can be used on a wide range of sheet basis weights and that the handsheet FA application technique has potential for exploration of lightweighting. We recognize that each mill's critical strength properties must be considered when lightweighting. Later work exploring the potential of many different synthetic dry strength additives shows that the various dry strength additives all increased all the strength properties we performed, but no one additive increased all properties the most. Specific work to look at the properties critical to a given application would be needed. The wet handsheet foam application method allows some bench scale investigation of this potential.

Production of a dose-response curve for each dry strength additive for WE and FA addition would have generated a much more complete picture of the potential of each additive and would have allowed comparison of the treatments at equal dose or equal cost. The abbreviated version of the work described in connection with Table III helped identify the additives most likely to yield good results in this application but required only a fraction of the handsheet production work.

We have identified some limitations of the wet handsheet foam application method. It is feasible as described only for square or rectangular handsheets that can be removed from the sheet mold after forming at a consistency of interest for applying foamed additives. Weighing the handsheet between each step to determine the exact percent solids at each stage and the exact weight of foam applied is sometimes necessary. These intermediate steps can often be skipped, especially if the foam is to be applied at as-formed consistency, which is our usual practice. The range of foam density that can be produced from a handheld homogenizer is limited but adequate for screening work. Our lab roll press seems to operate under pressure-limited conditions most of the time, which may not be appropriate for studying pressing variables. A limited amount of paper is produced, allowing only limited strength tests, as in all handsheet studies.

We continue to upgrade and improve this method.

CONCLUSIONS

We developed a useful method for applying foamed additives onto wet handsheet surfaces and drawing the additives into the sheets to simulate such a process on the forming section of a paper machine. It can apply foamed additives at handsheet consistencies of 8%–20%, for foam densities of 200–300 g/L and wet foam applications of 60 or more g/m², for handsheets of 40–150 g/m² basis weight. We have confirmed and extended the elevated sheet consistency results of Skelton [2]. We have demonstrated dose response, differentiated WE addition from FA addition, shown differentiated strength response based on water properties, and shown differentiated product-to-product strength response.

Handsheet production is relatively fast and low cost compared to pilot paper machine time or production paper machine time. The method appears to be broadly useful for screening potential foaming agents, dry strength additive products, wet-end water variables, and foam addition operating variables for the proposed process.

We also made conclusions concerning specific additive groups and their applicability for this process and reported significant increases in wet tensile properties.

The described method also appears to be feasible for studying the potential of lightweighting of recycled linerboard, which has significant potential payback opportunities. Specific strength properties of interest must be evaluated when considering lightweighting. **TJ**

ACKNOWLEDGMENTS

The authors wish to acknowledge the many individuals who contributed to the development of the handsheet coating device, method development, paper testing, and data analysis, and to Solenis management for permitting publication.

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ABOUT THIS PAPER

Cite this article as:
Bliss, T., Luo, M., Nicholas, M., *TAPPI J.* 20(1): 9(2021). https://doi.org/10.32964/TJ20.1.9

DOI: https://doi.org/10.32964/TJ20.1.9

ISSN: 0734-1415

Publisher: TAPPI Press

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About this journal

ABOUT THE AUTHORS

Application of foamed wet-end additives to paper in the forming section shows great potential to improve wet-end chemical efficiency. Although a few publications report work at the pilot paper machine scale, we felt a tool was needed to work at a much smaller scale, with more readily available resources.

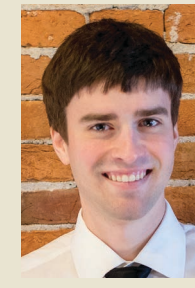
The most difficult aspect of this work was that the foam layer must be very thin and precisely applied, without contacting the wet handsheet. We kept the handsheet flat by forming on a very thin and flexible synthetic forming fabric and then applied the foam with a micro-adjustable blade that rides on fixed rails.

We found that foam assisted application does not impact formation and is not as sensitive to interference from dissolved materials in the white water. Interestingly, we were able to replicate the key trends identified during pilot scale trials with simple, readily available bench top lab equipment. This will greatly simplify development work.

Development of a path to lightweighting is a worthwhile goal for mills, with very high payback potential. We also see significant benefits for applications where wet-end additives are less effective due to interference from dissolved material in the white water. We are continuing to develop the method, and we are also exploring the application of other wet-end additives on other furnishes. We will also add foam-assisted application capability to our pilot paper machine, and we see benefits to handsheet and pilot scale research.

Bliss

Luo



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