Basis Weight Uniformity Of Lightly Needled Hydroentangled Cotton And Cotton Blend Webs

D.V. Parikh[1], Randall R. Bresee[2], Navzar D. Sachinvala[1], Legrand Crook[3] ,U. Muenstermann[4], Alfred Watzl[4], Don Gillespie[4]

[1]USDA, ARS, Southern Regional Research Center, New Orleans, Louisiana 70124, U.S.A.
[2]Department of Materials Science & Engineering, The University of Tennessee, Knoxville, Tennessee 37996, U.S.A.[3]John D. Hollingsworth on Wheels, Greenville, South Carolina 29602, U.S.A.[4]Fleissner GmbH, D-63329 Eglesbach, Germany

Correspondence to:
D.V. Parikh, Ph.D., email: Parikh@srrc.ars.usda.gov

Abstract

New nonwoven products containing cotton and Lyocell (Trademarked, Tencel), low temperature thermal-bondable bicomponent olefin/polyester, or comber noils were developed using needlepunching and spunlacing (hydroentanglement). Webs containing five different blends were prepared by either light needlepunching, or light needlepunching followed by hydroentangling. We acquired detailed basis weight uniformity measurements to learn about processing and the influence of fiber blend composition on web uniformity. Basis weight uniformity was evaluated without regard to web direction (“Total” uniformity), along the machine direction (MD uniformity) and across the cross direction (CD uniformity) at numerous size resolutions. We observed that blending manufactured fibers (either Tencel or olefin/polyester) with bleached cotton and comber noil substantially improved basis weight uniformity of both types of nonwovens. We also observed that subjecting needled webs to hydroentangling significantly improved Total and MD uniformities.

Introduction

Basis weight uniformity refers to the spatial distribution of basis weight in webs. When webs contain only fibers, uniformity refers to the spatial distribution of fiber mass in webs. Basis weight uniformity can be expressed in terms of the percent coefficient of variation (CV%) for the distribution of basis weight, and is typically computed after measuring the mass of numerous web samples of identical area.

Using image analysis techniques, basis weight uniformity can be estimated by computing the coefficient of variation of light intensity transmitted through numerous areas of a web. It can be done quickly using automated control of web motion and automated lens focusing without operator intervention [13]. Optical uniformity measurements have been shown experimentally and theoretically to compare favorably with basis weight uniformity measurements obtained by sample weighing [4].

Development of New Nonwoven Products

The objective of our development process was to create economical, high-quality, novel cosmetic pads and semi-durable bedsheets using new cotton blends in nonwoven webs formed by hydroentanglement. We addressed cost issues three ways. First, there is general economic advantage of using nonwoven materials rather than conventional woven or knitted fabrics. Second, cost savings should result from reducing areal density of these products. Cosmetic pads were developed to be 220 g/m^2 rather than the 250 g/m^2 pads available commercially, and bed sheets were developed to be 90 g/m^2 rather than the 120 g/m^2 woven sheets available commercially. Third, we reduced raw material costs by using cotton comber noil (10-15 mm staple length) along with conventional bleached cotton fiber (22-27 mm staple length) and unbleached greige cotton to save bleaching costs.

We addressed product quality by incorporating an environmentally benign, premium quality (although expensive) fiber, Lyocell (Tencel), as a minor fiber component. Tencel fibers of 2" staple length were used to impart a more silky hand to webs and improve fiber entanglement. A bicomponent fiber of olefin/polyster (Cellbond T255 from Hoechst Celanese Corporation), although expensive, was used to increase fiber bonding in webs by thermal fusion and to improve breaking and tearing strengths of bedsheets for semi-durability. A combination of bonding technologies (spunlacing and thermal bonding) was envisaged and hence used to achieve desired web properties. Thru-air drying was used for drying the wet fabric after hydroentangling and simultaneously achieving thermal bonding of the bicomponent fiber to improve fabric strength.

Methods

We analyzed 10 nonwoven webs prepared from five different fiber blends. Fibers used were bleached absorbent cotton, bleached absorbent cotton comber noil, Tencel, unbleached grey cotton and core/sheath bicomponent olefin/polyester. Fibers were weighed by blending hoppers with an electronic weight system and transferred to a conveyor, blend roll (with a 3-lag Kirschner Beater), and the Micro-Tuft Opener (MTO). The MTO consisted of (blending) feed rolls that transferred fiber to the cylinder in small tufts. Maximum opening and blending occurred in the MTO. Fiber was subsequently fed into a blending reserve and then conveyed by air to the Flockfeed Fine Opener with pedal-feed feed plates, and a 3-lag Kirschner Beater for fine opening. Finally, fiber was conveyed by air to the chute feed and the card.

All five blends were processed on a card line with a 2.5 m MASTERCARD, crosslapper, needle loom, and winder with slitter at Hollingsworth On Wheels in Greenville, South Carolina [3]. One sample of each blend was lightly needlepunched, whereas another sample of each blend was lightly needlepunched and then hydroentangled. Fabrics are described in Table 1.

Needlepunching was performed only lightly at a line speed of approximately 8 meters per minute on a Dilo Needle Loom. Light entanglement was needed to consolidate webs for easy handling during shipping and allow for subsequent hydroentanglement. The loom had two boards of needles, one having the straight line pattern and another having a random pattern, with 7,375 needles per square meter. The depth of needle penetration was about 0.30mm (0.012 inch).

Hydroentanglement (spunlacing) of needlepunched webs was conducted at Fleissener GmbH in Eglesbach, Germany [9-11] using an Aquajet Spunlace line with three-step hydroentanglement (with individual adjustment of water pressure for each manifold), dewatering, (water filtration, sanitizing water and recycling water), through-air drum drying, and winding. Spunlacing uses fine, high speed water jets to cause fibers to curl, entangle, and knot about each other. This increases web strength and imparts a different appearance to webs [5,8]. Each of the light needled webs (1N - 5N) was hydroentangled to produce hydroentangled fabrics (1NH - 5NH). Fabrics of 1NH and 2NH were meant for the end use of cosmetic pads whereas those of 3NH, 4NH and 5NH were for the end use of bed sheets.

We measured the uniformity of light intensity transmitted through webs after imaging the webs using an 8-bit monochrome CCD camera (256 gray levels). Optical uniformity was computed as the per cent coefficient of variation (CV%) in gray levels for each image area being considered. A larger CV% indicates that more optical (gray level) variation (i.e. larger standard deviation) and thus more basis weight variation exists in the web.

$$\textit{Optical Uniformity} = 100\,(\textit{Coefficient of Gray Level Variation})$$

$$\textit{Coefficient of Gray Level Variation} = \frac{\textit{Standard Deviation of Gray Levels}}{\textit{Mean Gray Level}}$$

Uniformity spectra were obtained by computing optical uniformity for image areas of varying size. Areas measured in this work ranged from whole images (25mm x 25mm) to individual pixels in images (45um x 45um). Uniformity spectra provide detailed information about webs and allow one to consider uniformity for the size range that is most pertinent to a web application. Webs generally exhibit more uniformity (smaller CV%) when larger web areas are considered since variations for small web areas are physically averaged when large areas are analyzed.

Uniformity was simultaneously measured three ways: (a) without regard to web direction (“Total” uniformity), (b) along the machine direction (MD uniformity), and (c) across the cross direction (CD uniformity).

We acquired detailed optical uniformity measurements to obtain basic information about the needlepunching and hydroentangling processes as well as the influence of fiber blend composition on the uniformity of needlepunched and hydroentangled webs. We assessed uniformity for various size resolutions and various web directions.

Basis weight uniformity measurements were acquired in a darkened room to reduce optical noise. A diffuse illumination source was used and the intensity of the light source was adjusted before measurements were acquired from a web so that the intensity of light transmitted through all webs was similar. One hundred web areas measuring approximately 25mm x 25mm were imaged for each web. Consequently, uniformity spectra included optical uniformity values that were computed from 100 data points for the largest resolution size (whole images), 23,040,000 data points for the smallest resolution size (individual pixels), and numerous intermediate resolution sizes.

Results

Table 1 shows the composition of blends in five webs. Since webs 1-4 were constructed from bleached absorbent cotton and comber noil fibers with absorbent Tencel fiber, these webs were instantaneously absorbent. Since web 5 contained grey cotton (unbleached non-absorbent), web 5N was non-absorbent whereas hydroentanlged web 5NH was absorbent, although not instantaneously absorbent as was the case for webs 1-4. Apparently, hydroentanglement cleaned the grey fibers sufficiently to make the web 5NH absorbent. As would be expected, thickness of the consolidated webs is significantly reduced on hydroentanglement. Needlepunched webs 3N and 4N were 1.9mm thick initially but were reduced to 0.7mm (3NH and 4NH) after hydroentanglement.

The influence of hydroentanglement on basis weight uniformity, the influence of blending a manufactured fiber (Tencel) with cotton, and the influence of several fiber blends (comparing webs 3-5) are discussed below.

Influence of Hydroentangling on Basis Weight Uniformity: All Webs

To evaluate the overall influence of hydroentangling on basis weight uniformity, we averaged CV% values at each size resolution for the five webs that were needlepunched and for the five webs that were needlepunched/hydroentangled. Uniformity spectra obtained in this way are shown in *Figure 1* for Total, MD and CD uniformities. These spectra clearly show that web uniformity depends on the size scale measured and webs exhibit less uniformity (larger CV% values) at smaller size resolutions. This occurs because the spatial distribution of fiber mass in webs varied on the size scale of individual fibers and entangled groups of fibers and these variations are physically averaged when large web areas are measured. *Figure 1* indicates that typical measurements of basis weight uniformity derived from cutting and weighing large web samples would be expected to yield relatively small variations in web uniformity (e.g. 2-4%) and are relatively insensitive to structural variations that exist on the small size scales of individual fibers and entangled groups of fibers.

Figure 1 shows that hydroentangling improved Total and MD uniformities (i.e. reduced CV%) at nearly all size resolutions. In contrast to this, hydroentangling reduced uniformity across the CD at all size resolutions.

Table 1. Description of Webs.

Web ID	Fiber Blend*	Process***	Target Basis Weight (g/m^2)	Web Thickness (mm)	
1 N	50% bleached No. 1 cotton 50% bleached cotton comber noil	Needled	220	3.7	
1 NH	50% bleached No. 1 cotton 50% bleached cotton comber noil	Needled and Hydroentangled	220	2.9	
2 N	40% bleached No. 1 cotton 40% bleached cotton comber noil 20% Tencel (3 den, 2 inch)	Needled	220	3.7	
2 NH	40% bleached No. 1 cotton 40% bleached cotton comber noil 20% Tencel (3 den, 2 inch)	Needled and Hydroentangled	220	2.8	
3 N	37.5% bleached No. 1 cotton 37.5% bleached cotton comber noil 25.0% olefin/polyester Bico T255	Needled	90	1.9	
3 NH	37.5% bleached No. 1 cotton 37.5% bleached cotton comber noil 25.0% olefin/polyester Bico T255	Needled and Hydroentangled	90	0.7	
4 N	32.5% bleached No. 1 cotton 32.5% bleached cotton comber noil 35.0% Tencel (3 den, 2 inch)	Needled	90	1.9	
4 NH	32.5% bleached No. 1 cotton 32.5% bleached cotton comber noil 35.0% Tencel (3 den, 2 inch)	Needled and Hydroentangled	90	0.7	
5 N	65% unbleached grey cotton* * 35% Tencel (3 den, 2 inch)	Needled	90	2.3	
5 NH	65% unbleached grey cotton 35% Tencel (3 den, 2 inch)	Needled and Hydroentangled	90	0.7	

* Fabrics from 1 NH and 2 NH were developed for cosmetic pads whereas fabrics from 3 NH, 4 NH and 5 NH were developed for bedsheets.
** Grey cotton was mechanically cleaned but contained natural hydrophobic oils and waxes.
*** Needlepunching was done lightly.

To help interpret uniformity spectra in Figure 1, optical images were acquired from webs to evaluate their structural variations. To illustrate web uniformity, images of Web 5 after light needlepunching are shown in Figure 2 (top). The reflected light image of the needled web (left) shows that fibers tend to be clustered into lightly entangled bunches. This produced local web areas that contained a higher areal density (brighter image areas) and often produced nearby web areas of lower areal density (darker image areas). This is seen more easily in the transmitted light image of the needled web (right) where web areas of lower density (brighter image areas) were often observed to be adjacent to web areas of higher density (darker image areas). Arrows denote web areas of low areal density that correspond to high brightness in the transmitted light image (right), darkness in the reflected light image (left) and are adjacent to high density fiber clusters in the reflected light images. Overall, these optical images support the use of optical uniformity measurements as reasonable estimates of basis weight uniformity for our web samples.

The bottom of *Figure 2* shows optical images of Web 5 after light needlepunching and hydroentangling. These images show that hydroentangling developed a basis weight variation that is periodic across the CD. Web areas that correspond to higher areal density are seen as bright columns in the reflected light image (left) and dark columns in the transmitted light image (right). Arrows denote web areas of lower density between high density columns and appear dark in the reflected light image and bright in the transmitted light image. *Figure 2* shows that hydroentangling reduced basis weight uniformity across the CD since hydroentangling caused fiber mass to vary periodically across the CD rather than being distributed in a more uniform manner. The distance between these structural repeat units across the CD was measured by optical microscopy to be 632 um. This distance is consistent with *Figure 1* which showed that hydroentangling reduced basis weight uniformity in all directions when uniformity is measured on the size scale of the periodic structure developed during hydroentangling. That is, hydroentanglement reduced basis uniformity most significantly for the smallest size measured (45 um x 45 um) and affected uniformity less for the next larger size (900 um x 900 um) and other sizes.

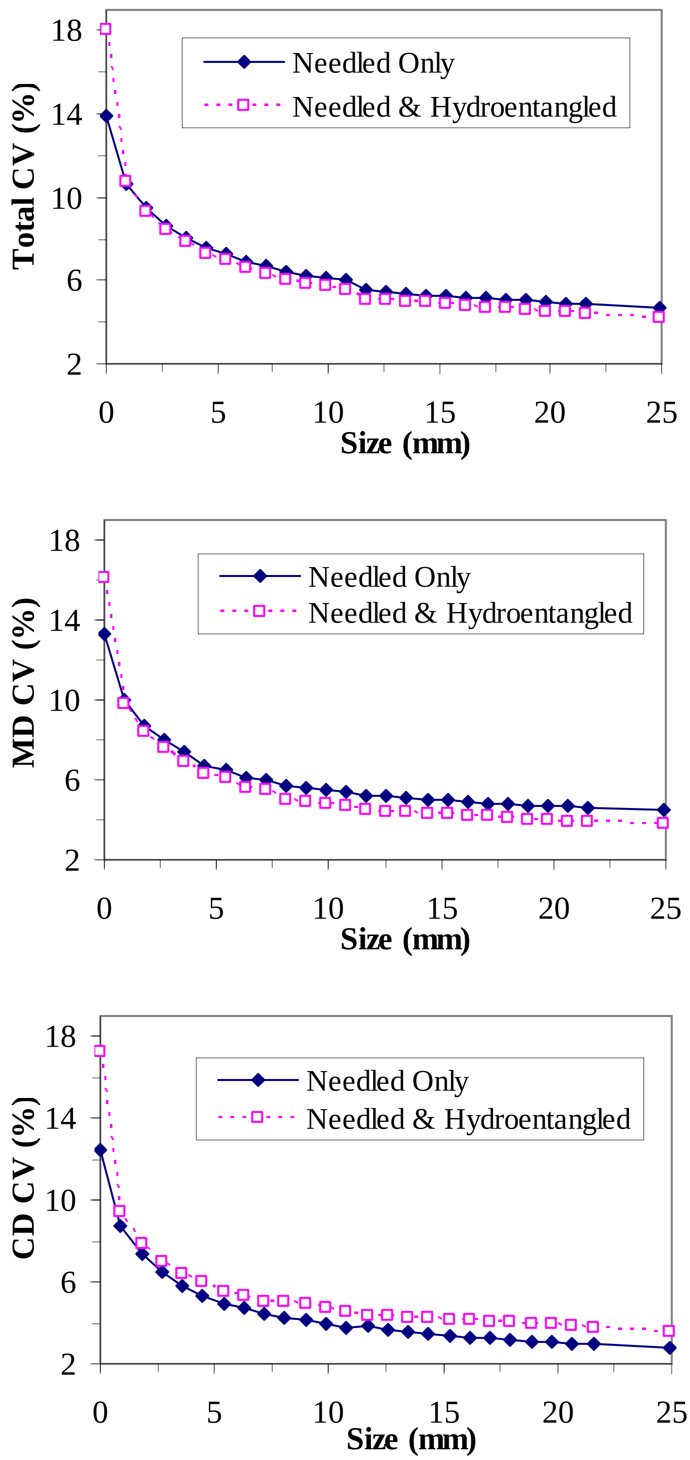


FIGURE 1. Web basis weight uniformity averaged for five webs:
Total uniformity (top), MD uniformity (middle) and CD uniformity (bottom).

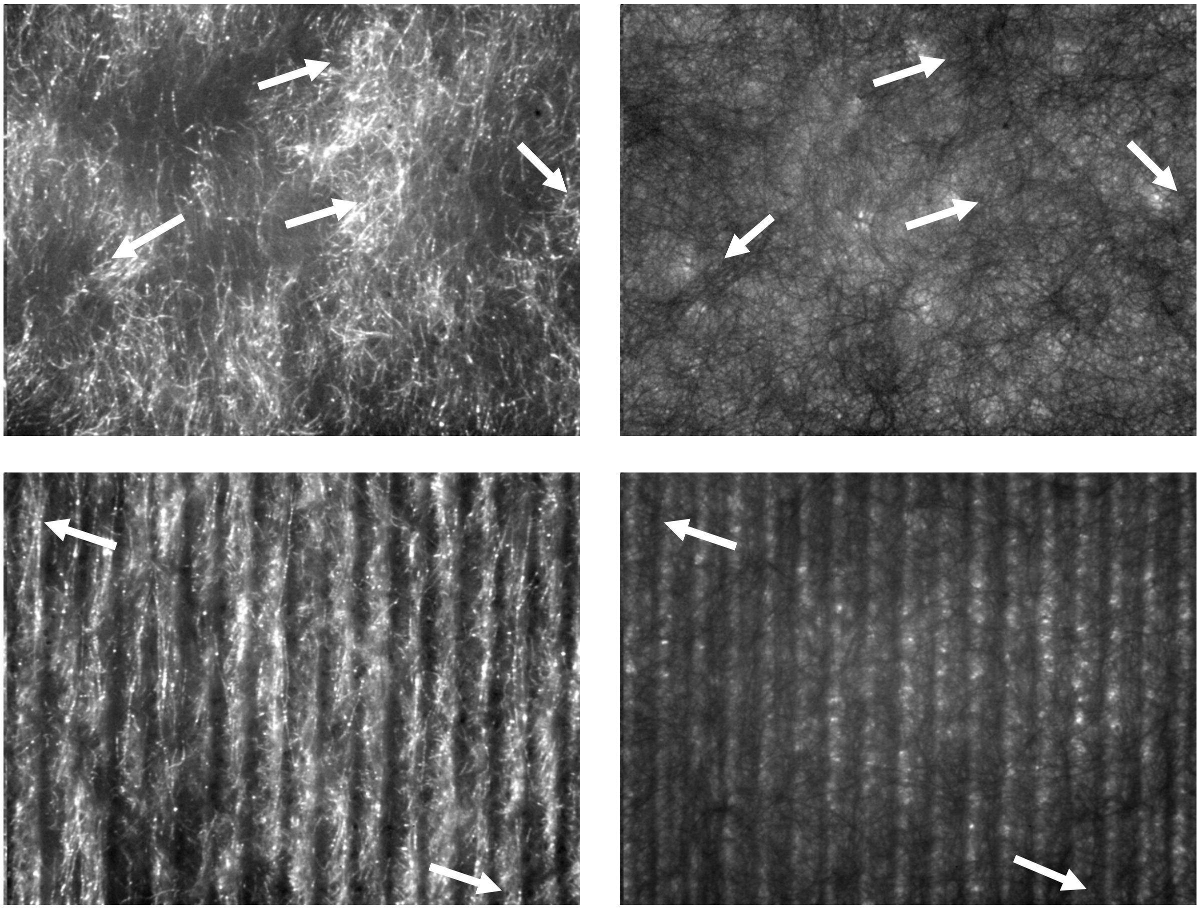
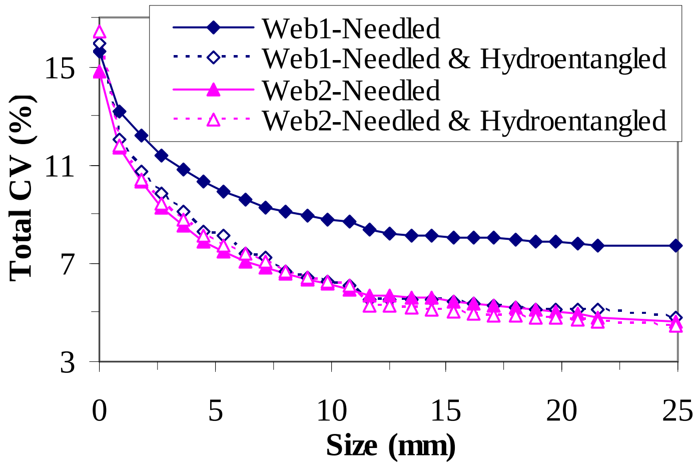


FIGURE 2. MD is vertical. Reflected light (left) and transmitted light (right) optical images of web 5 after needlepunching (top) and after needlepunching/hydroentangling (bottom): same web area (10.6 mm x 8.0 mm) in the top image pair and the bottom image pair.

Influence of Blending Tencel with Cotton: Webs 1-2

Webs 1 and 2 both contained Number 1 bleached cotton and cotton comber noil but Web 2 also contained 20% manufactured cellulose (Tencel) fibers [1,6,12]. Since the basis weights of these webs were the same, 220 g/m^2, differences in their basis weight uniformities can be attributed to local variations in basis weight. Consequently, these webs provided an opportunity to evaluate the influence on web uniformity of blending a manufactured cellulose fiber with cotton. Total basis weight uniformity data provided in *Figure 3* show that, after needling, Web 2 (with Tencel) exhibited considerably better basis weight uniformity than Web 1 (no Tencel) at all size resolutions. However, these differences nearly vanish after hydroentangling since Web 2 (with Tencel) exhibited only slightly better uniformity than Web 1 (no Tencel) at most size resolutions.



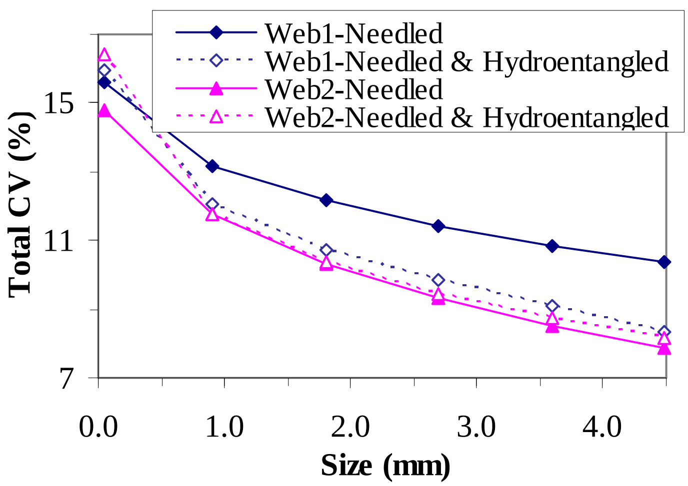
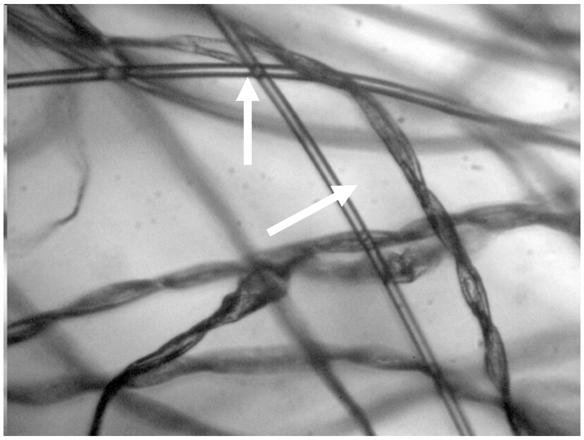


FIGURE 3. Total web basis weight uniformity for webs 1-2: whole uniformity spectrum (top) and small sizes only (bottom).

Overall, *Figure 3* shows that blending Tencel with cotton greatly improved basis weight uniformity in lightly needled webs but hydroentanglement nearly eliminated the difference. That is, basis weight uniformity analysis conducted over a large size range showed that hydroentangling influenced web uniformity enough that fiber blending had little consequence on basis weight uniformity.

We thought that differences in Total basis weight uniformity in lightly needled webs might have been related to the influence of fiber bending rigidity on fiber motion during opening, blending and needling. Optical microscopy of individual fibers in webs revealed that Tencel fibers were bent less frequently than cotton fibers. This is illustrated in *Figure 4* (left), which shows Web 2 after needling. Arrows are used in this figure to label Tencel fibers, whereas cotton fibers are easily recognized by their convolutions [7]. The higher bending resistance of Tencel fibers leads us to expect that Tencel fibers would have tendency to become less entangled in webs. *Figure 4* (right) also illustrates that the surface of Tencel fibers was significantly more uniform and smoother than cotton fibers. More uniform and smoother fiber surfaces would be expected to result in easier disentanglement once fiber entanglement occurs since fiber-to-fiber friction is reduced. Increased fiber bending resistance and reduced fiber friction for Tencel fibers is a reasonable explanation for improved basis weight uniformity in Web 2 (with Tencel) compared to Web 1 (no Tencel).



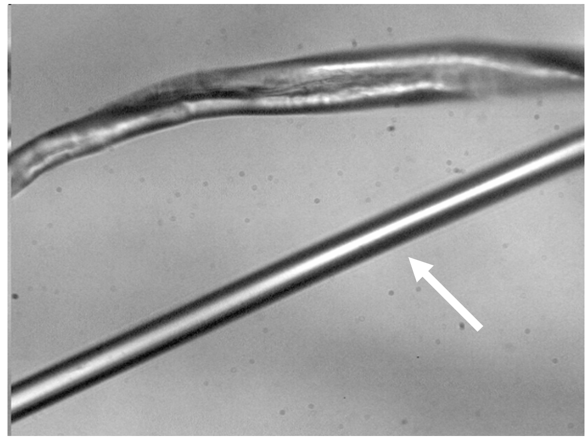


FIGURE 4. Optical images of web 2 after needlepunching:
Web area in images are 505 um x 379 um (left) and 200 um x 150 um (right).

Basis weight uniformity spectra in the MD for Webs 1 and 2 (not shown) were quite similar to spectra for Total uniformity. That is, uniformity in the MD at all size resolutions was considerably better for Web 2 than for Web 1 after light needling but their difference was greatly reduced after hydroentangling.

Figure 5 shows that CD basis weight uniformity for Webs 1-2 was substantially different than Total and MD uniformity. This figure shows that Web 2 (with Tencel) was more uniform in the CD than Web 1 (without Tencel) after light needling although their difference was small. *Figure 5* also shows that the difference between CD uniformity for Webs 1 and 2 after hydroentangling was insignificant.

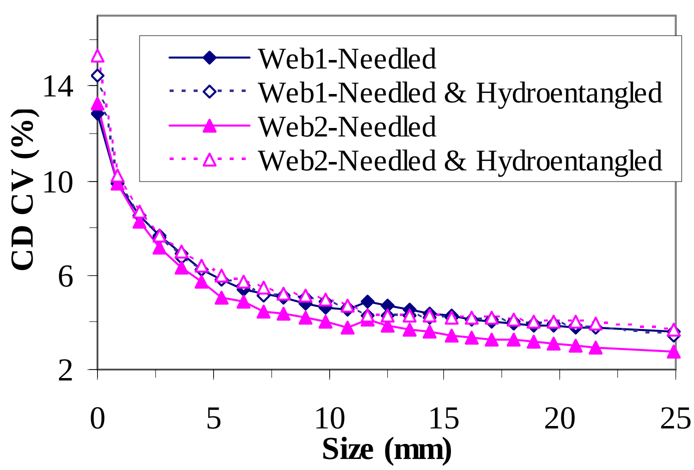


FIGURE 5. Web basis weight uniformity in the CD for webs 1-2.

Influence of Blend Composition: Webs 3-5

The previous discussion provided evidence that blending a manufactured cellulose fiber (Tencel) with cotton substantially improved basis weight uniformity in lightly needled webs. We also observed that hydroentangling the needled webs greatly reduced uniformity differences associated with fiber blending. In this section, we examine additional fiber blend compositions. Webs 3-5 (basis weight = 90 g) contained a manufactured fiber along with cotton. Web 3 contained 25% olefin/polyester bicomponent fiber to provide additional bonding due to thermal fusion. Webs 4 and 5 both contained 35% Tencel fiber as well. Webs 3 and 4 contained Number 1 bleached cotton and cotton comber noil whereas Web 5 contained unbleached grey cotton.

First, we consider the needlepunching process for these three webs. *Figure 6* shows that Web 3 (bleached No.1 cotton and comber noil with bicomponent fiber) exhibited the best Total and MD uniformity whereas Web 5 (unbleached grey cotton with Tencel) was the least uniform. These observations suggest that the bicomponent fiber facilitated development of more uniform fiber spatial distribution than Tencel fiber. Figure 6 also suggests that unbleached grey cotton did not perform as well as bleached cotton during needling.

Examination of individual fibers in webs using optical microscopy revealed that, like Tencel fibers, bicomponent fibers were more resistant to bending and exhibited smoother surfaces than cotton. Consequently, we expect that increased fiber bending resistance and reduced fiber friction for bicomponent fibers might have resulted in improved basis weight uniformity as observed with Tencel fibers.

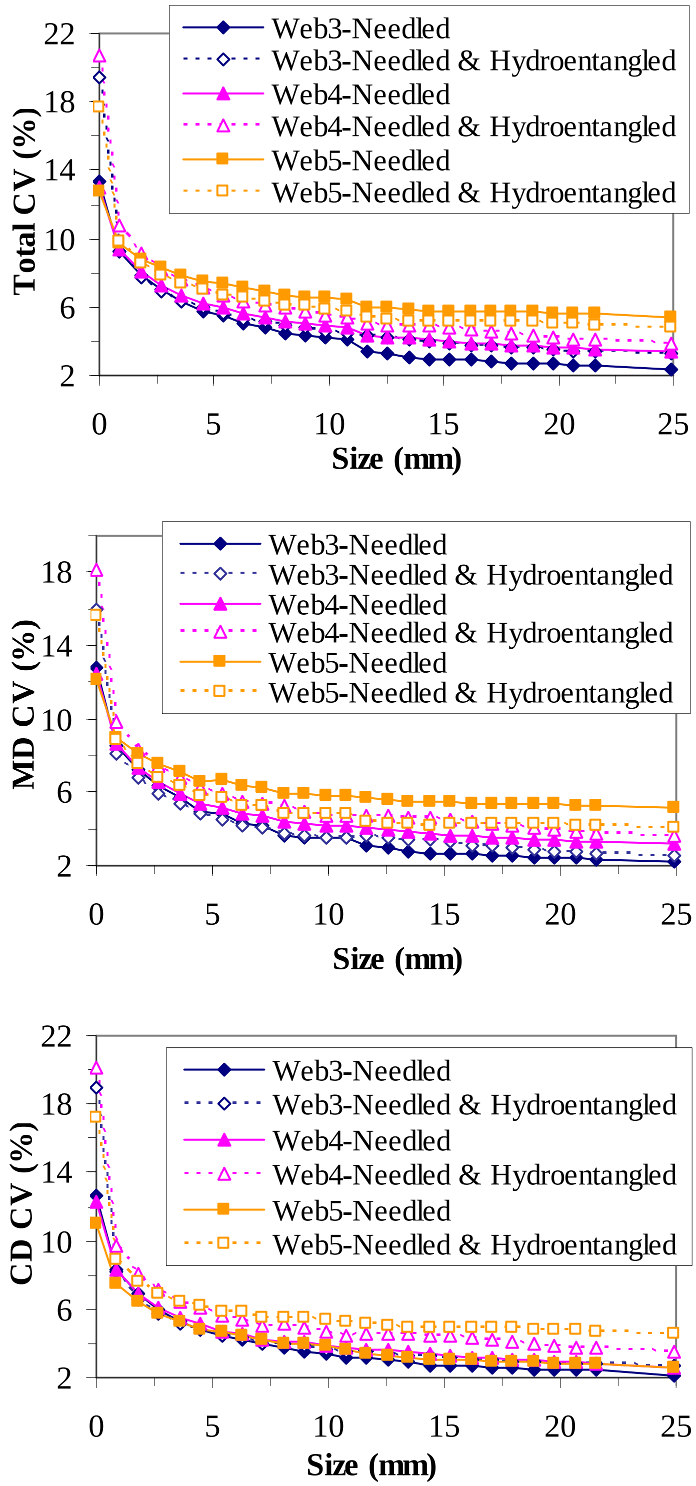


FIGURE 6. Web basis weight uniformity for webs 3-5: Total uniformity (top), MD uniformity (middle) and CD uniformity (bottom).

Next, we consider the hydroentangling process for Webs 3-5. *Figure 6* shows that hydroentangling reduced basis weight uniformity substantially at small size resolutions for all three webs. The cause of this is likely development of small-scale periodic basis weight variations during hydroentangling as discussed previously. At larger size resolutions, hydroentangling generally improved uniformity for the web produced with unbleached grey cotton (Web 5).

Total and MD uniformities for Webs 3-5 were similar to one another but were different than uniformity in the CD as observed for Webs 1-2. *Figure 6* indicates that process variations which influenced basis weight uniformity across the CD in needled webs were comparable for the three webs even though their fiber compositions differed. That is, basis weight uniformity across the CD after needling apparently was dominated by processing rather than by fiber composition. On the other hand, *Figure 6* shows that hydroentangling clearly produced differences in CD uniformity that were related to differences in fiber composition.

To obtain a simplified view of the effect of fiber composition on basis weight uniformity, we removed the influence of size resolution from our data. This was accomplished by computing a sum of CV% values for all sizes recorded in each uniformity spectrum. *Figure 7* characterizes basis weight uniformity in this manner. This figure shows that blending a non-cotton fiber with cotton improved overall basis weight uniformity after light needling. That is, the Total and MD CV% sums for Web 1 (cotton only) after needling were substantially larger than other needled webs (cotton plus non-cotton). However, *Figure 7* shows that this difference was greatly reduced by hydroentangling. That is, the Total and MD CV% sums for Web 1 were more comparable to other webs after hydroentangling although they remained larger than other hydroentangled webs.

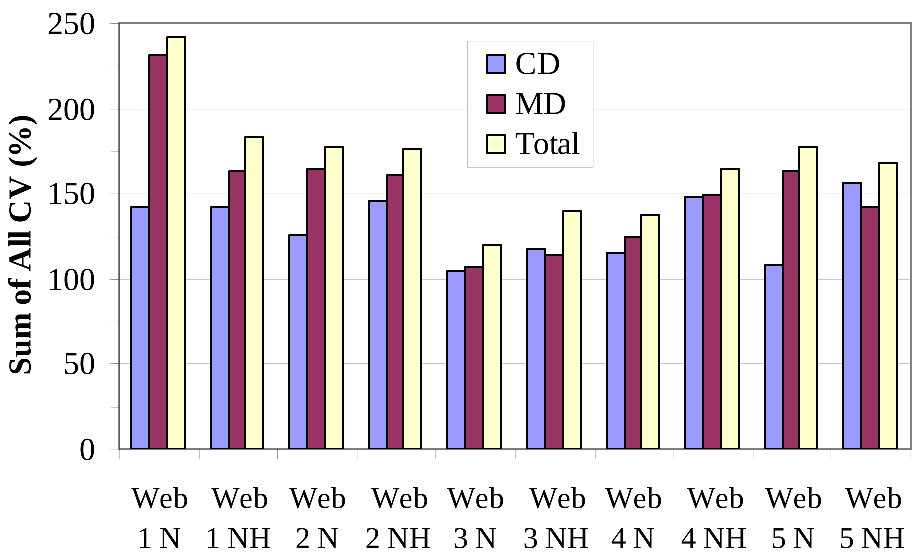


FIGURE 7. Web basis weight uniformity summed for all size resolutions measured: N denotes needled whereas NH denotes needled and hydroentangled.

Figure 7 also shows that substituting unbleached grey cotton for Number 1 bleached cotton and comber noil resulted in overall uniformities that were similar if the webs were hydroentangled. That is, the summed CV% for Web 4 (No. 1 bleached cotton and comber noil) and Web 5 (unbleached grey cotton) were similar after hydroentangling even though Web 5 was less uniform than Web 4 before hydroentangling. We observed that grey cotton cleaning occurred during hydroentangling. Cleaning increased grey cotton absorbency (Web 5 NH was absorbent whereas Web 5 N was not absorbent). This finding is of commercial interest since the cost of unbleached grey cotton is substantially less than the cost of bleached cotton. However, the benefit may be partially offset by the need to install a more powerful water filtration system to filter out debris extracted from unbleached grey cotton during hydroentanglement.

Conclusions

Webs were developed to explore possible economic advantages of replacing conventional woven fabrics with nonwoven webs, using cotton comber noil to reduce material costs, and using Tencel or bicomponent fibers to reduce web basis weights. Ten webs were prepared from five fiber blends containing cotton using light needlepunching or light needlepunching and hydroentangling. Target end uses for this work were premium quality cosmetic pads and bedsheets. Optical imaging was used to estimate the basis weight uniformity of webs at numerous size resolutions for Total uniformity, MD uniformity and CD uniformity.

We observed that blending a manufactured fiber (Tencel or olefin/polyester bicomponent fiber) with bleached Number 1 cotton and bleached cotton noil improved basis weight uniformity in needlepunched webs. The manufactured fibers probably were more resistant to bending than cotton and this may have reduced the amount of fiber entanglement that occurred during processing. It was also thought that the manufactured fibers probably had less fiber-to-fiber friction than cotton and this may have reduced the amount of fiber disentanglement that occurred during processing after fiber entanglement developed. Both of these effects may have contributed to the improved web uniformity observed when Tencel or olefin/polyester bicomponent fibers were blended with cotton.

Subjecting needled webs to hydroentangling significantly reduced uniformity differences associated with fiber blending. Hydroentangling also reduced basis weight uniformity in any web direction at small size resolutions and in the CD at all size resolutions because webs developed structural variations that were periodic on a small size scale across the CD.

References

[1] Achwal, W.B.; Gleanings from German Literature: Lyocell Fiber, Colourage, vol. 47/issue 2, pp. 40-42, 2000

[2] Coppin, P.; The Future of Spunlacing, *Nonwovens World*, vol. 10/issue 6, pp. 60-67, 2002

[3] Crook, L.; Dry-Laid Systems, Nonwovens: Theory, Process, Performance, and Testing, Ed. Turback, A.F., TAAPI Press, Atlanta, GA, pp. 155-170, 1993

[4] Huang, X.C., and Bresee, R.R.; Characterizing Nonwoven Web Structure Using Image Analysis Techniques. Part III: Web Uniformity Analysis, *Journal of Nonwovens Research*, vol. 5/issue 3, pp. 28-38, 1993

[5] Parikh, D.V., and Patience, D.; Prospects of a USP Monograph on Surgical Spunlace Fabrics, Proceedings, IDEA 04 Conference, Miami Beach, Florida, 2004

[6] Sayed, U., Pratap, M. R., Singh, A. S., Rane, Y. N., Pawar, A. L.; Lyocell: Fiber of Future, Colourage, vol. 49/issue 10, pp. 33-36, 2002

[7] Segal, L., and Wakelyn, P.; Cotton Fibers, Handbook of Fiber Science and Technology: Fiber Chemistry, Ed. Lewin, M. and Pearce, E. M., Marcel Dekker, Inc., New York, USA, pp. 809-908, 1985

[8] Seyam, A.M., and Shiffler, D.A.; An Examination of the Hydroentangling Process Variables, *International Nonwovens Journal*, vol. 14/issue 1, pp. 25-33, 2005

[9] Watzl, A.; The Spunlace Process – Technology for Cotton Fibers, *International Textile Bulletin*, vol. 4, 2002

[10] Watzl, A.; AquaJet Spunlace System for Low-Cost Production of Multi-Layer Composites, *International Fiber Journal*, vol. 19/issue 1, pp. 41-43, 2004

[11] Watzl, A.; Production of Multi-Layered Composites of Air-Laid/Spunlaced Structures, AATCC Review, vol. 3/issue 6, pp. 11-14, 2003

[12] Wilkes, A.; Tencel – Versatile, High Performance Fiber for Nonwovens, *Chemical Fibers International*, vol. 53/issue 6, pp. 412-414, 2003

[13] Yan, Z., and Bresee, R.R.; Flexible Multifunction Instrument for Automated Nonwoven Web Structure Analysis, *Textile Research Journal*, vol. 69/issue 11, pp. 795-804, 1999