Article:

Edwards, JV, Mao, N, Russell, SJ et al. (7 more authors) (2015) Fluid handling and fabric handle profiles of hydroentangled greige cotton and spunbond polypropylene nonwoven topsheets. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 586020. ISSN 1464-4207

https://doi.org/10.1177/1464420715586020

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

Fluid handling and fabric handle profiles of hydroentangled greige cotton and spunbond polypropylene nonwoven topsheets

J Vincent Edwards[1], Ningtao Mao[2], Stephen Russell[2], Edmund Carus[3], Brian Condon[1], Doug Hinchliffe[1], Lawson Gary[3], Elena Graves[1], Alvin Bopp[4] and Yiyi Wang[2]

[1]Southern Regional Research Center, USA
[2]Performance Textiles and Clothing Research Group, University of Leeds, UK
[3]T.J. Beall Company, USA
[4]Southern University, New Orleans, USA

Corresponding author: J Vincent Edwards, USDA, Southern Regional Research Center, 1100 Robert E. Lee Blvd., New Orleans, LA 70124, USA. Email: vince.edwards@ars.usda.gov

Abstract

Wettable nonwoven topsheets are traditionally spunbond polypropylene nonwoven fabrics. The fluid handling performance of hydroentangled greige cotton nonwovens was studied to determine their suitability for topsheet applications based upon analysis of fluid rewet, strikethrough, and acquisition properties; and the relative contributions of nonwoven cotton's cellulosic and wax components to hydrophobic and hydrophilic fluid transport properties are addressed. It was observed that mechanically cleaned greige cotton nonwovens exhibit certain fluid handling properties that are similar to polypropylene spunbond-meltblown topsheets, partly as a result of the residual wax content. Subsequently, the surface polarity, swelling, and moisture uptake of 100% greige cotton and 50:50 blends of greige cotton and polypropylene hydroentangled nonwovens were studied in comparison with the performance of a commercially available 100% polypropylene spunbond-meltblown topsheets. The surface polarity, swelling, and wettability values obtained from electrokinetic and

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

water contact angle analysis were found to be in agreement with the hydrophobic polypropylene topsheets. Additionally, comfort assessment was undertaken based upon fabric handle profiles using the Leeds University Fabric Handle Evaluation System, which is an objective evaluation based on the quantification of fabric buckling deformations. Of the fabrics studied in this work, 50:50 greige cotton/polypropylene hydroentangled fabrics were the softest as determined by the Leeds University Fabric Handle Evaluation System and exhibited fluid handling properties consistent with the requirements of commercial topsheets.

Keywords

Fluid handling, fabric handle, greige cotton, nonwoven, topsheet

Introduction

Cotton in absorbent nonwovens

Cotton fibers are complete plant cells that grow out from cotton seeds.[1] The fiber is composed mainly of cellulose molecules,[2] which are found in the primary and secondary cell walls, mostly in the form of small crystallites. The crystallites are stabilized by conventional O–H. . .O hydrogen bonds as well as weaker van der Waals forces and C–H. . .O hydrogen bonds.[3] Greige cotton is unbleached cotton that retains waxes and pectin in the outer regions of the fiber that would normally be removed by traditional bleaching and scouring processes. Specifically, hydrophobic lipids and pectin account for approximately 1%–2% by weight of the fiber,[1] and they are associated with the primary cell walls and outer protective cuticles (Figure 1). Normally, raw cotton is scoured and bleached prior to use in consumer products such as continence management devices removing the waxes and pectin on the surface of the cotton fiber.

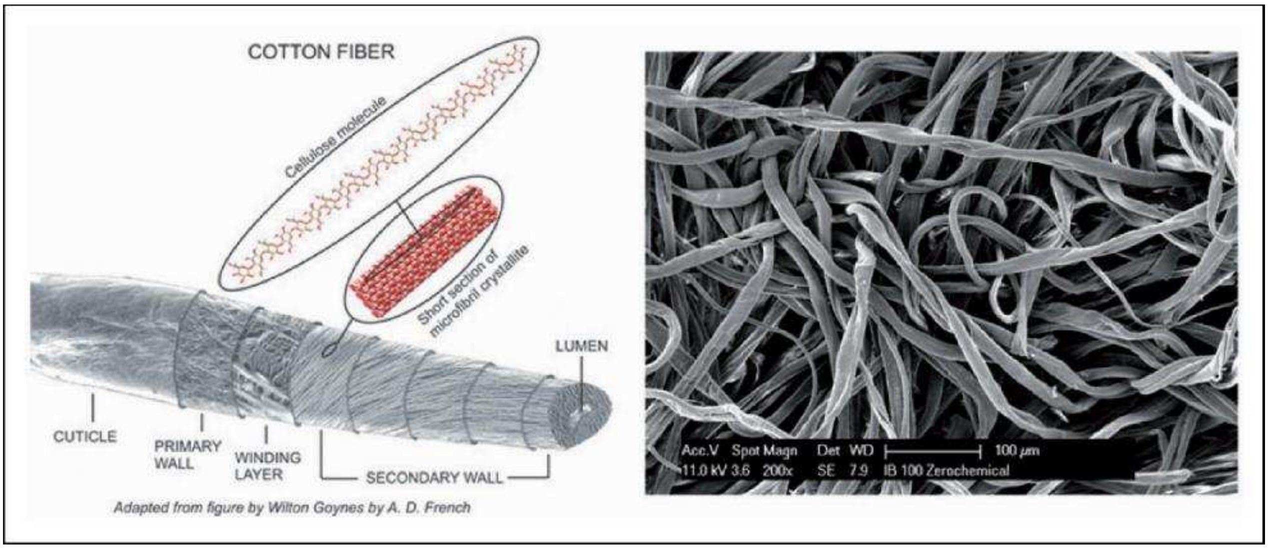

Figure 1. (a) Morphology of the cotton fiber as portrayed from a montage of SEMs[1] and (b) SEM image of 100% greige cotton hydroentangled nonwoven.

Both cotton and polypropylene (PP) are currently used as raw materials by the nonwovens industry to manufacture absorbent products, but the latter is consumed in much larger quantities and is very commonly encountered in fabrics used as top sheets incontinence management devices. The cotton used by the nonwoven industry is generally bleached prior to being made into fabrics and consists of lint, gin motes, linters, comber noils, and so-called other cotton textile processing wastes.

The purpose of a nonwoven topsheet is to permit rapid inlet of the liquid in to the interior of the absorbent product without allowing liquid to strike-back against the wearer's skin. Therefore, it is common practice to utilize substrates made from materials with inherently low water absorption in top-sheets, provided they are water permeable, to minimize the potential for water to be retained near to the surface of the product.

The polarity of bleached and scoured cotton is such that the fibers are relatively hydrophilic, whereas PP is inherently hydrophobic. To promote water inlet, PP topsheets are chemically treated or otherwise surface modified to modify wetting behavior, without affecting the bulk water absorption properties of the material. Based on fiber preparation and nonwoven processes that expose the hydrophilic cellulosic component of greige (unbleached) cotton fiber to water absorption,[4–6] it is instructive to understand if greige cotton is able to balance the competing technical requirements of a functional nonwoven topsheet.

PP has predominantly been utilized in nonwoven top sheets in continence management products throughout the world for decades and is produced for nonwovens at a rate of approximately 50 million tons annually.[7] Cotton's current use in nonwovens is estimated to be approximately 2% (by volume/ weight) of the total fiber consumption in nonwovens, and most of the cotton used at present in absorbent nonwovens is bleached.[8] The potential to use highly cleaned greige (non-bleached) cotton in nonwoven absorbent products could afford an economical source of cotton nonwovens with retention of properties associated with soft hand similar to traditional apparel fabrics.

Fabric handle in continence management devices containing cotton

Given that continence management products are usually worn next to the skin in a moist environment, liquid and vapor management properties as well as tactile comfort properties are of major importance.[9,10] Skin is the largest organ in the body and has constant interactions with the nervous, immune, and endocrine systems (the neuro-endocrine-immunocutaneous system).[11] Skin adopts a varied microclimate at the cutaneous-textile interface depending upon the nature of the material,[12,13] and there are many issues in achieving an optimum for this with incontinence management devices. However, it is generally accepted that nonwoven fabrics can be engineered to adapt to the cutaneous-textile microclimate and meet sensorial requirements.

One of the goals of absorbent nonwoven product development is the improvement in fabric comfort while retaining functional performance. Cottenden et al.[14] have described improved methodologies for modeling friction, pressure, and shear at the skin-fabric interface with care sheets and incontinence pads. Moreover, in recent years, a variety of approaches have been reported to assess tribology at the skin-fabric interface with both nonwoven and woven materials.[15] Studies have been reported dealing with the skin-fabric interactions in the presence of pressure, shear, and friction as well as the influence of epidermal hydration on friction of human skin against textiles.[16,17] Thus,

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

previous work in this field has involved both human subjects and instrumental measurements.

Subjective assessment of fabric hand frequently varies from individual to individual and can be affected by personal opinions and subjective preferences.[18] Results of instrumental evaluation using methods such as the Kawabata evaluation system for fabrics and fabric assurance by simple testing are also not necessarily objective because of their dependency on the use of statistical data,[19] artificial neural network outputs,[20] or relationships between measured fabric mechanical properties and the subjective hand preferences of human panels using reference fabrics.

Tactile comfort relates to the sensory perception that a person receives when the human hand deforms a fabric by stretching, squeezing, and rubbing[21] and such fabric deformations involve buckling in multiple directions[22] rather than one-dimensional fabric deformation or fabric bending as measured by the Kawabata evaluation system for fabrics and fabric assurance by simple testing. In handle assessment methods based on extraction,[18,23,24] a fabric is forced through a narrow opening such as a ring or nozzle creating deformation in multiple directions similar to that occurring in the human hand during subjective evaluations. However, the resultant quantitative assessment of fabric handle is based on statistical principal component analysis and the conclusions of subjective assessment. Additionally, the random fabric deformations that occur in the extraction systems can lead to issues of reproducibility. In the Fabric Touch Tester,[25–27] tactile comfort is evaluated based on multiple fabric bending deformations rather than the fabric responses during buckling deformation. Existing approaches as outlined here do not quantify the recovery of the fabric following initial deformation, which is known to affect the tactile perception in subjective fabric hand evaluations.[22]

Assessment of tactile comfort at the skin–fabric interface has required satisfying a variety of different criteria, one of the purposes of which has been to improve the objective evaluation of fabric handle. The criteria for evaluating clothing comfort have been reviewed in relation to woven and nonwoven fabrics[28] as well as the developments that have been made in bridging the gap between subjective and objective handle measurements. The limitations of existing fabric handle evaluation systems have been addressed by development of the Leeds University Fabric Handle Evaluation System (LUFHES).[29] This system subjects the fabric to controllable biaxial buckling

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

deformations that mimic the multidirectional buckling deformations taking place during subjective fabric hand evaluation. Specifically, the method involves subjecting a specimen of fabric formed into a cylindrical shape to twisting, stretching, and compression buckling deformations as well as friction evaluation before determining fabric handle indices from the derived data. The fabric deformations in LUFHES, which mimics the fabric deformation subjective fabric hand evaluation and links to the four classes of cutaneous mechanoreceptive afferents in human skin, are quantified by measuring the energy consumed during the fabric deformation process.[22]

As a potential alternative to existing fabric substrates, nonwoven top sheets containing greige cotton must meet the combined requirements of liquid handling and fabric handle if they are to be industrially implemented. At present, there is limited data on these aspects of nonwoven fabrics containing greige cotton, which this study aims to elucidate. Specifically, the key fluid handling characteristics of strikethrough (or liquid inlet), rewet, and fluid acquisition properties of greige cotton will result from a complex combination of the molecular interactions affecting both hydrophobicity and hydrophilicity as well as structural features of the greige cotton. Additionally, this study includes objective measurement of the handle of fabrics containing greige cotton using the LUFHES system.[29] To provide greater industrial context, nonwoven fabrics containing a blend of greige cotton and PP were included in the study, as well as a light-weight PP spunbond-meltblown (SM) nonwoven fabric utilized in continence management devices.

Materials and methods

Raw materials and fabric preparation

A commercially available bale of pre-cleaned greige cotton (True Cotton™) was acquired from T. J. Beall, LLC and mechanically cleaned through a proprietary process (http://www.tjbeall.com/naturalfibers-nonwoven/true-cotton). This is a mechanical, non-aqueous process that removes non-cotton impurities

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

consisting of small plant parts and field trash (non-lint or foreign matter) to a level of 99.99% purity. To obtain surfactant containing (penetrant-treated) samples, mechanically cleaned nonwoven greige cotton was treated by Huntsman Chemical with penetrant (ULTRAPHIL®CO) to 53%–87% wet pick-up and then dried at 140 °C for 1 min. The final add-on was 0.8% w/w solids.

Carded and hydroentangled nonwoven fabrics containing mechanically cleaned greige cotton fiber were produced using a pilot production line at Tru¨ tzschler Nonwovens (Wolfsgartenstraße 6, 63329 Egelsbach, Germany). For reference purposes, a 100% PP 16 g/m^2 SM nonwoven (S 1/4 spunbond, M 1/4 meltblown) fabric (or SM PP fabric) suitable for use in hygiene applications was sourced.

Extraneous matter extraction. Cotton wax content measurements were obtained by dichloromethane extraction using an Automated Solvent Extractor (Dionex) at a temperature of 100 °C and a pressure of 10.7 MPa. The extraction liquid (20 mL) was poured into aluminum weighing boats and allowed to evaporate. The edges of the weigh boats were cut away with scissors to provide an unobstructed edge-on view of the wax surface for contact angle measurement. The edges of the weigh boats were removed providing a planar surface for contact angle measurement.

Liquid handling properties. Liquid strike-through, rewet, and liquid acquisition tests were performed by Marketing Technology Service, Inc, Kalamazoo Michigan. According to EDANA/INDA WSP 70.3 (former ERT 150) and WSP 70.7(former ERT 153), the liquid strike-through time involves determining the time taken for a known volume of test liquid (simulated urine) applied to the surface of a test piece of nonwoven coverstock, which is in contact with underlying standard absorbent pads to pass through the fabric. Rewet was undertaken according to EDANA/ INDA WSP 80.10 (former ERT 151) and WSP 70.8 (former ERT 154), in this procedure, the wet back of synthetic urine through a prepared sample onto a filter paper is determined. After applying a defined volume of liquid upon the prepared sample (strike-throughtime test), a simulated baby weight is automatically lowered onto the specimen at a predefined speed and dwell time. Using a specific filter paper and an electronic balance, the amount of liquid that transfers back through the specimen’s surface into the filter paper is determined. The liquid acquisition

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

test evaluates in real time how effectively liquids penetrate into the absorbent core of the absorbent device at any flow rate. A 0.9% saline solution is applied to the specimen at a specific volume and flow rate. The dynamic change of the total volume of both leakage (and fluid acquisition) and overflow liquids over the duration of the testing was obtained.

Moisture uptake

The moisture content of the fabrics was measured using modified ASTM D629-99 and AATCC 20A2000 methods. The modification involved using an infrared lamp to dry the materials rather than a laboratory oven stated in the standard methods. The sample was conditioned overnight in a humidity chamber with relative humidity of 70% and a room temperature of 23 °C. Moisture measurements were made on 1 g specimens (N 1/43) based on weight loss of the fabrics and were determined using an infrared moisture balance (Kett FD 240, manufactured by Kett Electric Laboratory in Tokyo, Japan). The balance was set for automatic wet-based moisture with a drying temperature of 110 °C.

Fabric polarity and swelling behavior: Streaming zeta potential experiments were carried out with an electrokinetic analyzer (Anton Paar, Ashland Va.) using a cylindrical cell developed for the measurement of fibrous samples. For each measurement, a fiber plug was placed between the Ag/AgCl hollow cylindrical electrodes of the cylindrical cell. The pH dependence of the zeta potential was investigated with the background electrolyte of 1 mM of KCl solution.

Swelling behavior of the fabrics was also measured using the electrokinetic analyzer with the same cylindrical cell template mentioned above. A 0.65 g sample was loaded into the cell and quickly rinsed with electrolyte solution. The flow rate was adjusted to the range of 60–100mL/min by compression of the sample to remove trapped air. The pH of the sample was about 5.5 and was adjusted to 9.0 by adding 0.1 N NaOH solution.

Contact angle. Contact angle (ɵ) of fabric specimens was measured using a VCA Optima instrument. A droplet of 1µl distilled water was deposited onto the surface of the sample, and the contact angle was measured manually after the droplet stabilized. Briefly, five discrete points were marked on the perimeter of the droplet image to

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

define its boundary, and the contact angle was taken from the angle between a baseline and the tangent line of the droplet at the baseline. Contact angles from both the left and right contact points were determined and, in the experiments reported herein, the two values were averaged to give the reported contact angle. Twelve replicates of the measurements were made from different regions of each sample. The contact angle of cotton wax was also measured using the same method. Cotton waxes were obtained by dichloromethane extraction of 5 g samples using a Dionex Automated Solvent Extractor Model ASE200 (Thermo Scientific, Marietta, OH). The extractions were held at constant temperature and pressure of 100°C and 1500 psi, respectively, and samples were extracted two times with a total collection volume of approximately 40 mL. Each extraction liquid, of 20 mL, was poured into an aluminum weighing boat, and the solvent allowed to evaporate. The edges of the weighing boats were removed to provide a planar surface for the contact angle measurement.

Fabric handle testing using LUFHES. Fabric handle was objectively evaluated using LUFHES.[29] Six fabric specimens, three in the machine direction (MD) and three in the cross direction (CD) of each nonwoven fabric were tested. Cyclic compression buckling of 30%, cyclic shear deformation of 5° twisting, and friction properties of the three nonwoven fabrics were evaluated during the biaxial deformations of the fabrics. Six fabric handle descriptors and indices are defined based on the energy consumed either to deform a fabric or to recover the deformation from the deformed state as defined below.[29]

Fabric sponginess (SP): the extent to which a fabric spontaneously recovers from deformation when the external deformation force is withdrawn (elasticity).

Fabric crispness (CR): the level of unrecoverable permanent deformation produced under external deformation force.

Fabric flexibility (FL): the resistance to recovery of the original dimensions after deformation by an external force.

Fabric stiffness (ST): the resistance to deformation by an external force.

Fabric softness (SF): the combined effect of the resistance to deformation and the resistance to the recovery subject to an external force.[29]

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

The total fabric handle value (TFHV) is defined as:[29]

$$TFHV = SP + CR + ST$$

Thus, the greater the TFHV value, the more energy is required to deform the fabric and recover the deformed fabric. An additional parameter referred to as fabric smoothness is defined as the dynamic fabric-tofabric self-friction coefficient, which is the coefficient of dynamic friction between the fabric and itself.

Whiteness index. Whiteness index was determined according to AATCC 110-1989 using a Milton Roy color Mate color analyzer (Milton Roy Company, USA).

Air permeability. Air permeability was determined according to ASTM D 737 giving units of $cm^3/s/cm$ (N=2).

Tensile strength. Tensile strength was determined both in the MD and CD using ASTM D-5035, which is based on cut strip testing of samples.

Results and discussion

General properties of nonwovens

All three nonwoven fabrics are designed to assess the potential for use as topsheets in feminine/adult hygiene and incontinence or baby diaper products. The properties of the two greige cotton hydroentangled fabrics are given in Table 1.

The tensile strength of the hydroentangled greige cotton fabric was three times higher than the greige cotton/PP fabric despite a difference in basis weight of only 40%. As expected given the presence of residual wax in the cotton, blending with PP increased the whiteness index. Both the air permeability and water vapor transmission rates of the greige cotton fabric were within the lower range suitable for use in occlusive wound dressings and absorbent incontinence nonwovens, thus being consistent with materials worn near the skin.[30, 31]

Electrokinetic and water contact angle analysis

Polarity is one of several parameters in absorbent materials that influence functional fluid transport along with fabric porosity, charge (zeta potential), bulk density, and chemical composition. We have previously shown how electrokinetic models of topsheet and acquisition distribution layers can be helpful in predicting and designing materials by relating polarity, charge, and swelling to fluid transport properties.[32] The moisture uptake (% MC) and the electrokinetic results including the fabric surface polarity $_{(plateau),}$ swelling (ĀC), rate of swelling (k), and related factors for all materials including the 100% greige cotton and 50/50 greige cotton/PP blend are shown in Table 2. The zeta (~) potential titration assesses the surface charge based on pH, and the planar portion along the x-axis of the plot is designated as the zeta plateau value ($_{plateau}$), which is a reflection of the relative hydrophilic versus hydrophobic character of the fabric. When evaluated in absorbent fabrics, $_{plateau}$ is relevant to the wide pH range found in human urine. The relative fiber and fabric surface polarity $_{(plateau)}$ of the 100% greige cotton and the 50/50 greige cotton/PP blend was −27 and −61, respectively (Table 2). This is in contrast with the material's swelling (swell ratio, see Table 2) which is increased in the 50/50 greige cotton/ PP blend by approximately 4% over the 100% greige cotton, and the observed swelling is consistent with cellulosic/synthetic blends increasing web interstitial space and modulating pore size.[6,8] In practice, the required degree of swelling will depend on the fabric design, composition, and intended function.[32,33]

We have previously shown that the magnitude of the $_{plateau}$ is a reflection of the degree of hydrophobicity and is consistent with water contact angle magnitude for greige cotton blends with polyester.[32] Contact angle measurements were performed on hydroentangled (HE) fabrics of both greige cotton and greige cotton with all residual waxes being extracted. The results of the contact angle measurements are given in Table 3. Contact angle measurements on fabrics after wax extraction were not possible due to rapid absorbance of the droplet in to the substrate. Table 3 indicates similarity in the apparent hydrophobicity among the PP and the greige cotton surfaces (contact angles ranged from 135.8 to 141.1). The wax components from the extraction with a nonpolar solvent produced a lower contact angle within the range observed for PP film.

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

Table 1. Properties of griege cotton nonwoven samples.

Composition	Area density (g/m^2)	Tensile Strength MD	Tensile strength CD (N/5	Whiteness AATCC11	Coefficie of friction	Air permeability ASTM D ($cm^3/s/cm^2$)	Water transmissio rate ($g/h/m^2$)
100% greige cotton fine	35	17.4	10.6	39.8	1.2	472	37
50/50 greige cotton/PP fine	25	6.28	4.4	66	1.13	505	39.7

MD: machine direction; CD: cross direction; PP: polypropylene.

Table 2. Electrokinetic parameters obtained from hydroentangled 100% greige cotton nonwoven (I), 50/50 greige cotton/PP nonwoven (II), and spunbond-meltblown (SM) PP nonwoven (N = 3).

Sample ID	Area density	Moisture content	Isoelectri point	Plateau potential	Swell test (min^{-1})	0 (mV)	oo (mV)	A	Swell ratio	R2
I	35	8.48	2	-27	0.018	-32.7	-29.4	0.101	1.054	0.939
II	25	4.41	2.2	-61	0.011	-54.6	-45.3	0.171	1.098	0.961
Polypropyle			2.5	-32	0.032	66.051	41.843	0.3695	1.259	0.989

Stable water droplets did not form immediately upon contact on the greige cotton HE fabrics, which delayed securement of an equilibrium position. Water droplets were initially unstable on contact, such that the shape and size varied for several seconds, which may be due to uneven distribution of residual waxes on the cotton fiber surfaces combined with heterogeneous local fabric density. Once the water droplet appeared stable, the contact angle was measured. It is recognized that when a droplet is placed on a surface it is initially not in an equilibrium state, and it will spread until equilibrium is achieved, which is a dynamic process. The process is complex and relies not just on surface tension but also other properties of the liquid and the fabric surface, including irregularity in the wax distribution, fabric density, and liquid viscosity. To better understand the wetting phenomenon, two experiments were carried out using the dynamic capture feature of the VCA apparatus. In Dynamic Capture, a droplet is deposited on a surface and multiple images are recorded for subsequent analysis. Figure 2(a) shows real-time snapshots of contact angle measurements of griege cotton and demonstrates the irregularity of the surface. Figure 2(b) illustrates the

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

dynamic changes in contact angle on a droplet placed directly on the extracted wax over a 15s duration, and it was observed that the contact angle exponentially decreased as a function of time (Figure 2(b)). The decrease in contact angle observed with time indicates the dynamic process between the residual wax coating present on the greige cotton fibers and the water.

Table 3. Contact angle results for griege cotton nonwovens of this study accompanied by some results on PP samples, as detailed in the "Materials and Methods" section. Probabilities were determined to be at $P < 0.01$.

Sample		SD	CV* (%)
PP film	95.2	4.5	4.7
PP SM fabric (70g/m^2)	135.8	3.3	2.4
50/50 greige cotton	141.1	6.6	4.7
100% greige cotton	140.9	5.6	4.0
Residual waxes extracted from greige cotton	83.9	6.8	8.1

PP: polypropylene; PP SM: polypropylene spunbond-meltblown. *Coefficient of variation.

Because of the morphology of greige cotton fiber and the variation in exterior residual wax contents after hydroentanglement, the surface can be regarded as having irregularities or roughness, which is capable of influencing water contact angle. In the models of Wenzel[34] and Cassie and Baxter,[35] a real surface is considered as one containing a number of micro grooves that effectively increase specific surface area. In the Wenzel model,[34] the liquid contacts the surface including the area inside putative grooves below the water droplet. Since the total contact area of the liquid on the surface is fixed by surface tension/ energy of the component materials, the increased surface area per unit geometric area yields a larger contact angle. In the Wenzel model,

$$\cos\Theta_a = r \cos\Theta_s$$

where

Θ_s = contact angle on a smooth (or ideal) surface, i.e. in this study the cotton wax and the PP film.

Θ_a = the apparent contact angle on a real (rough) surface, i.e. in this study the three nonwovens being

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

considered, and

r = roughness of the surface = actual area/geometric area.

A roughness factor can readily be determined by measuring the contact angles of a liquid on a smooth surface (a film) and a rough surface (fabric). In the Cassie–Baxter model,[35] the liquid does not fill the grooves and the total contact is a composite of that with the solid surface and that with the air that fills the grooves in between. In this case,

$$\cos \Theta_a = \phi \cos \Theta_s + \phi - 1$$

and is sometimes written as

$$\cos \Theta_a = r\phi \cos \Theta_s + \phi - 1$$

Note that, Θs and r have the same meaning as before and ϕ is the fraction of the surface contacted by the liquid.

Note that as ϕ –> 1 (full coverage), the Cassie equation reduces to the Wenzel equation. The literature is not conclusive as to which model to select and under what circumstances.

Figure 2. (a) Real-time photographs showing surface roughness and the contact angle on the surface of 100% greige cotton HE fabrics. (b) Plot of water contact angles measur$_t$ed on 100% greige cotton wax. The contact angles decreased as a function of time and were fit to an exponential decay: $\theta = A + Be^{-\frac{t}{c}}$, terms A, B, and C represent: A =Θ at time = ∞; B = change in Θ from t = 0 to time = ∞; and C = decay constant, i.e. the time for 36.8% of the change to occur. From A and B, Θ_0 (Θ at time = 0) =A + B.

Based on the contact angles measured for the three nonwoven fabrics, the fabric roughness factors of these two fabrics, “r” in the Wenzel equation, and ϕ in the Cassie equation were determined, as r = 7.91 and ϕ = 0.31 (PP nonwoven) and $\phi = 0.32$ (greige cotton nonwovens). ϕ denotes the fraction of coverage of each component under the water droplet, which in this study is either the more hydrophobic component (cotton wax and PP) or air. Thus based on the Cassie equation, it can be concluded that 32% of the water droplet coverage is the wax-coated fiber, and the other 68% is air.

Water binding

The exposed cellulose of the greige cotton fibers increases the wettability of the material and should be considered for water binding properties.[6] The binding of water to cotton cellulose can be characterized as being present in three different states including: (1) strongly bound or non-freezing water, (2) anisotropically constrained or perturbed water, and (3) unperturbed water or water undergoing isotropic motion.[36,37] As previously noted,[32] the water binding properties were influenced by the fiber structure, from a crystalline to microfibrillar state. Crystalline cellulose (crystallites of 36 chains) is characterized as being low water binding.[37–40] However, ordered microfibrillar cellulose, which comprises cellulose crystallites,[39] possesses surface hydroxyls presenting accessible water binding sites where penetrating water forms a monolayer (termed non-freezing water) at a level of (0.1 g/g cotton).[37,38] The presence of a strongly bound monolayer of water on cotton has been consistent historically with thermal calculations (90 cal/g) approximating that of the heat of fusion for ice, and validating the hydrogen bonding forces to cellulose.[38,40–43] From this state further water sorption then assumes the character of capillary condensation and has been characterized as free water, i.e. perturbed and unperturbed water.

Although these are fundamental considerations, they collectively make cotton a uniquely absorbent cellulosic material. However, this study underlines the importance of the surface portions of the greige cotton fiber that include the lipids or nonpolar components that would typically be removed by scouring and bleaching and yet retained on the surface of the material as shown in the SEM in Figure 1. Although little has been reported to bring a better understanding of their role in moisture management, these surface, low-percentage components of the greige cotton fiber confer interesting properties relevant to moisture management and incontinence layer design.

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

Based on numerous past studies that characterize the role of water binding in cotton, it is notable that greige cotton possesses approximately 8% moisture content (equilibrium moisture is about 7.5%) and has most of its water strongly bound as non-freezing water under ambient conditions. Here it is observed to be 8.48%. Thus, it is likely that most of the water associated with swelling of the greige cotton/PP blend is free unperturbed water. This is likely as well as it has previously been shown that the density of interfacial water (strongly bound water) on cellulose is increased when it is perturbed. This property improves the overall wettability of the greige cotton/synthetic blends and may be seen as contributing synergistically to the swelling properties observed, i.e. as the cotton is wettable so is it absorbent.

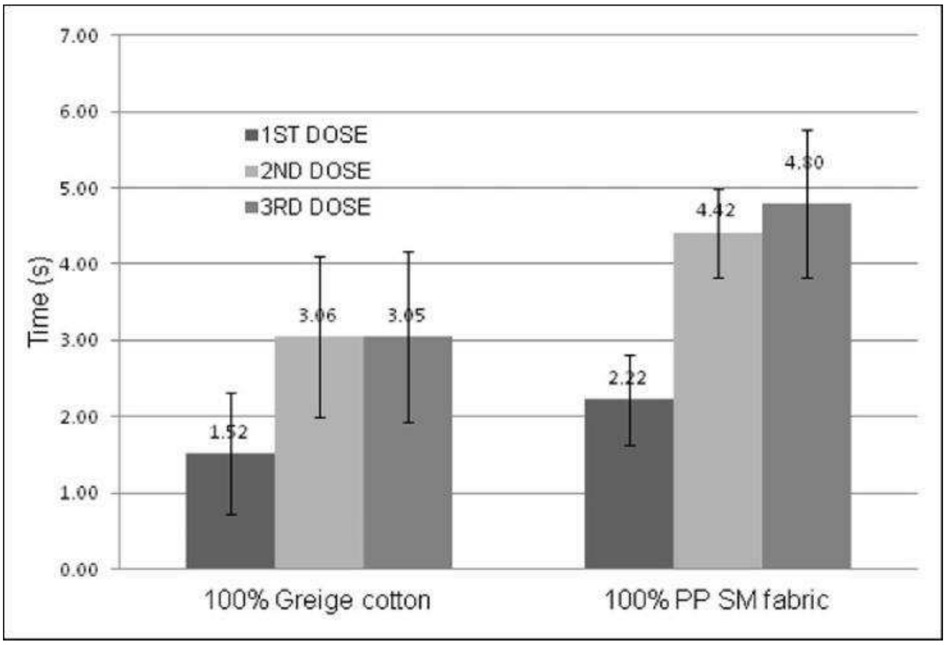

Figure 3. Multi-dose liquid strikethrough test using the same filter paper for each dose. Surfactant-treated 100% greige cotton nonwoven compared with 100% PP SM fabric.

Strikethrough, rewet, and fluid acquisition of penetrant-treated greige cotton fabrics

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

Spunbond PP fabrics used as topsheets in continence management products are typically treated with surfactant to facilitate liquid inlet and transport from the skin to contiguous hydrophilic cellulosic layers. It is interesting that surfactant-treated PP has been shown to have a zeta potential[44] similar to that determined for the greige cotton nonwoven of this study, and it is interesting to speculate on the surfactant-like functionality of naturally occurring polar and nonpolar components in the greige cotton nonwoven, i.e. lipids, pectin, and proteins in the primary cell wall of the fiber. Surfactant facilitates rapid strikethrough, low rewet, and efficient fluid acquisition and distribution to the absorbent core. It is also noteworthy that the design of absorbent incontinence materials has historically been based on engineering a relatively hydrophobic surfactant-treated top sheet with a hydrophilic cellulosic acquisition and distribution layer.

To further evaluate the effect of a synthetic surfactant on the greige cotton activity, its fluidic capacity at rewet, strikethrough, and acquisition was assessed. These performance assays are used to identify functionality important to the skin–textile interface. The performance of penetrant-treated mechanically cleaned greige cotton in the multiple strikethrough tests, i.e. modified EDANA/INDA WSP 70.3 (Figure 3), which uses the same filter paper, was found to be similar to PP-based samples. Thus, considerable improvement in strikethrough was observed over PP samples when penetrant was used. Since it has been demonstrated that co-existence of hydrophilic and hydrophobic yarns in woven fabrics can facilitate directional wicking of water,[45] it is feasible that the amphiphilic nature (having both a hydrophobic and hydrophilic phase) of the greige cotton nonwoven probably could help the liquid wicking in a nonwoven structure and thus play a role in facilitating strike-through. This property also contributes to the ability of absorbent materials in continence management devices to swell as observed previously.[32,33] The polar gradient between layers of topsheet and acquisition distribution layers facilitates fluid movement in incontinence products as a function of the relative polar (hydrophobic and hydrophilic) differences identified between individual layers of the commercial incontinence products.[33] An amphiphilic gradient has also been characterized in greige cotton nonwovens and blends containing polyester.[32] However, in greige cotton nonwovens, the amphiphilic mechanism is based on hydrophobic channels or interstitial spaces distributed randomly in the material that make contact with the absorbent cellulosic portions which make up the major part of the nonwoven, facilitating rapid liquid wicking. This model of polar gradients is analogous to the one proposed by Gupta and coworkers[46,47] where synthetic and cellulosic fibers (as cotton) together improve absorbency by

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

increasing web interstitial space and modulating pore size. However, in the case of 100% greige cotton, the waxes afford the hydrophobicity versus a more hydrophobic synthetic fiber when combined with scoured and bleached cotton.[46]

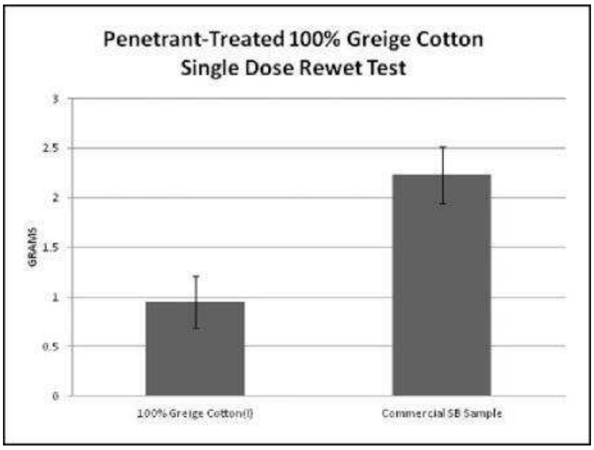

Figure 4. Results of rewet evaluation on surfactant-treated 100% greige cotton nonwoven.

It is notable as seen in Figure 4 that rewet measured by a modified (EDANA/INDA WSP 80.10) increased over penetrant untreated samples with addition of penetrant to the cotton, but it was still half the volume of the SM nonwoven fabric used as a comparison in the test. Low rewet values are associated with the ability to both absorb and hold water in the absorbent preventing it from coming in contact with the skin. The cellulosic component of the cotton and its lower elasticity may affect this. Richer[48] has noted that rewet around 0.11 to 0.13 mL as measured at 2.5 kPa is undetected by the skin.

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

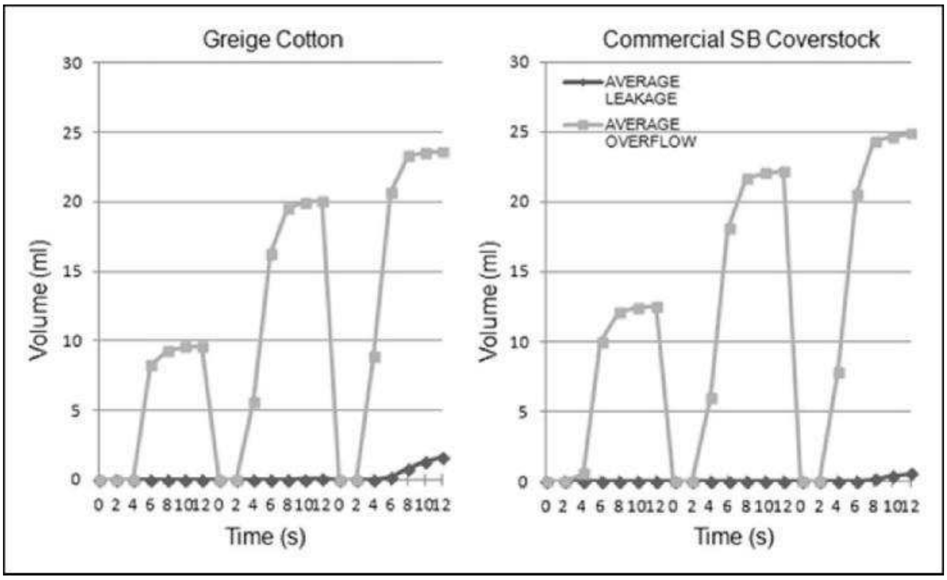

Figure 5. Liquid acquisition profiles of 100% greige cotton compared with polypropylene top sheet.

The penetrant-treated 100% greige cotton nonwoven was also an improvement in fluid acquisition over untreated samples shown previously. As seen in Figure 5, the acquisition overflow and leakage were significantly less than the PP samples following multiple insults. Thus, this series of performance tests of rewet, strikethrough, and acquisition with penetrant-treated greige cotton nonwoven fabrics demonstrate greige cotton to be highly functional and similar to spunbonded PP top sheets in its fluidic management properties.

Fabric handle analysis

Subjective fabric hand evaluation is a process of sensing and discrimination of the mechanical forces exerted on the human hand by deformed fabrics through four classes of the skin's cutaneous mechanoreceptive afferents.[18] The fabric handle analysis of this study is based on LUFHES, which is an objective measure that mimics fabric deformations occurring in the subjective fabric hand evaluation process. LUFHES discriminates the fabric handle indices using the amount of energy consumed in producing different types of deformations. The details of the results are shown in Table 4, and a comparison of TFHVs for the three nonwovens examined in this study is shown in Figure 7.

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

Table 4. Comparison of the fabric handle indices of the three nonwoven fabrics expressed as energy of deformation.

Fabric name			SP	CR	FL	ST	SF	TFHV = SP+CR+ FL+ST	SN[a]
			(1E-04 Joule)						
100% greige cotton HE fabric	MD	Mean	20.50	5.27	10.65	38.65	53.16	75.07	1.060
		SD	1.09	0.36	0.33	1.39	1.71	2.01	0.199
	CD	Mean	11.08	3.74	6.88	22.60	32.47	44.30	–
		SD	0.37	0.33	0.28	0.82	1.17	1.10	–
	Whole	Mean	15.79	4.51	8.77	30.62	42.81	59.69	1.060
		SD	4.75	0.82	1.91	8.08	10.4	15.47	0.199
50:50 greige HE fabric	MD	Mean	10.48	1.72	3.27	20.13	26.44	35.60	0.825
		SD	0.34	0.07	0.12	0.87	1.26	1.07	0.091
	CD	Mean	5.69	1.22	2.03	11.37	15.55	20.31	–
		SD	1.65	0.18	0.24	1.49	1.24	2.26	–
	Whole	Mean	8.08	1.48	2.65	15.78	20.99	27.96	0.825
		SD	2.59	0.28	0.64	4.49	5.54	7.85	0.091
SM PP nonwoven	MD	Mean	50.81	11.27	16.85	80.35	100.42	159.28	0.330
		SD	4.19	0.68	1.06	5.58	7.02	9.05	0.024
	CD	Mean	42.94	8.67	15.66	65.79	83.31	133.06	0.419
		SD	0.89	0.73	0.60	0.60	0.71	1.36	0.012
	Whole	Mean	46.87	9.97	16.25	73.07	91.87	146.17	0.374
		SD	4.65	1.42	0.92	7.97	9.47	14.62	0.047

MD: machine direction; CD: cross direction; SP: fabric sponginess; CR: fabric crispness; FL: fabric flexibility; ST: fabric stiffness; SF: fabric softness; TFHV: total fabric handle value; SN: fabric smoothness.

[a]The SN value (or the dynamic friction coefficient) in the cross direction (CD) of the two hydroentangled nonwoven fabrics is unavailable.

The SM PP fabric was found to be less flexible than the other two hydroentangled greige cotton fabrics since the amount of external energy consumed in recovering the deformed PP SM fabric was much greater than that in the two hydroentangled fabrics. The energy consumed in recovering the deformed PP SM fabric was about two-fold greater than that in the 100% greige cotton fabric (cotton) and six-fold greater than that in the 50:50 greige cotton/PP HE nonwoven (cotton/PP) fabric. Consistent with this finding, the PP SM fabric was also much stiffer than the two hydroentangled fabrics. The amount of external energy consumed to deform the PP SM fabric was more than two times that of the griege cotton fabric and about four and a half times that of the 50:50 greige cotton/PP fabric.

In terms of fabric softness, as shown in Table 4, the 50:50 greige cotton/PP was softer than the 100% griege cotton fabric, which may be partially due to its smaller fabric mass per unit area; it was also much softer than the PP SM fabric. The energy consumed both to deform the PP SM fabric, which was the least soft, and to recover the deformation of the deformed fabrics was much greater than that in the two hydroentangled fabrics. It was more than two times greater than in the 100% griege cotton fabric and about four-fold that found in the 50:50 greige cotton/PP fabric.

The enhanced softness of the greige cotton fabrics compared with the PP may also be due to the effect of hydration and the swelling capacity. There is a significant change in the mechanical properties of micro-crystalline cellulose when the moisture content exceeds 5%, and it is clear that water makes cellulosic materials more easily deformed as the moisture content increases.[49] It may be added that it has also been observed that a 5% moisture level in cotton cellulose corresponds to a water of hydration of one water molecule per cellobiose unit, which is sufficient to completely hydrate the surface of crystalline cellulose.[39] These studies are also consistent with a recent report on freezable moieties obtained in cellulosic gels at hydration levels of 5% or greater which also produced increased strength.[50] It is also worth noting that as the least absorbent sample, the PP SM fabric was the least soft since the energy consumed both to deform the PP SM fabric and to recover the deformation was much greater than for both the two hydroentangled greige cotton fabrics. Finally, the interaction of cotton fibers with the smoother surface of the PP fibers in the hydroentangled 50:50 greige cotton/PP fabric may tend to increase fabric flexibility and decrease fabric stiffness.

The fabric handle for smoothness is shown in Figure 6. As fabric smoothness is defined as the dynamic friction coefficient of fabric-to-fabric, less energy consumed is directly proportional to the degree of smoothness, i.e. lower values indicate smoother fabrics. Owing to the filamentous composition and thermal calendaring, the PP SM fabric exhibited a smoother surface than both

Proc IMechE Part L: J Materials: Design and Applications 0(0) 1–13 DOI: 10.1177/1464420715586020
Date received: 26 November 2014; accepted: 17 April 2015; published: 22 May 2015

hydroentangled fabrics, which contained staple cotton fibers and had apertured structures. This difference in surface smoothness can be expected to influence the water contact angle results shown in Figure 3, since it effectively affects surface roughness at a macroscopic level. The PP SM material produced the smallest coefficient of friction, which was less than half that of the 50:50 cotton/PP fabric (in the MD) and about a quarter of that of the 100% greige cotton fabric (in the MD). It was noted that the coefficient of friction of the 100% greige cotton fabric was much greater than 1, which is consistent with both the SEM and water contact angle evidence. Moreover, there were most likely surface deformations (e.g., biting points, indentations, etc.) in the cotton fabric surface under smaller pressure, which would be expected to increase friction.

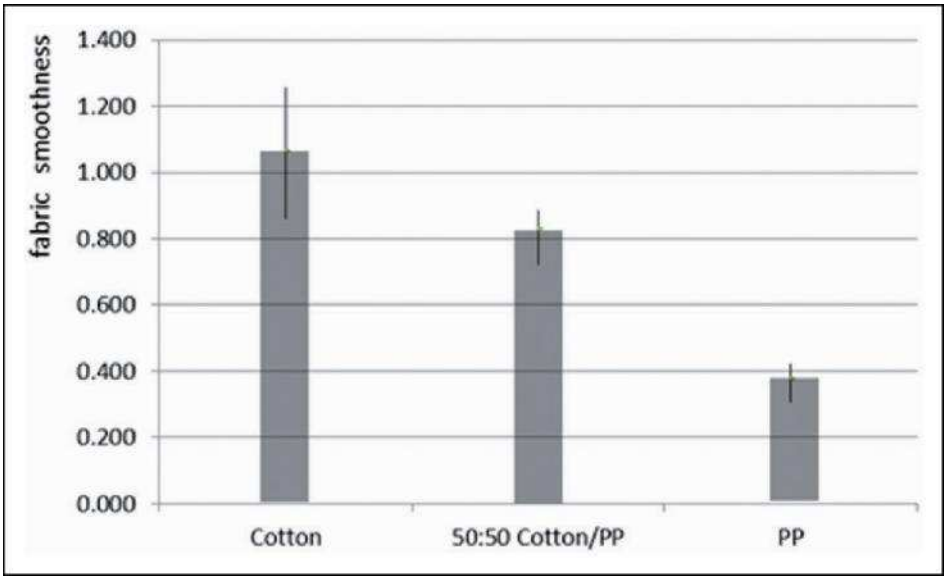

Figure 6. Comparison of the fabric smoothness

It is well known that textile fabrics including nonwoven, woven, and knitted fabrics are inherently anisotropic giving rise to non-uniform properties in different directions.[51,52] The properties of the three nonwoven fabrics studied in this paper are no exception to structure anisotropic properties. In this regard, it is important to note that the standard deviation of the TFHV of the three fabrics studied was in a relatively large range (between 10% and 28% of their average TFHV). This standard deviation was mainly due to the anisotropy of the fabric properties in MD and CD. Most of the standard deviation of each indices in the same direction (i.e., repetition tests of three specimens in either MD or CD) was small (consistently within 5% of the average value of its corresponding indices), and there is a significant difference between the average values of each indices in different directions, i.e. frequently the average value of each indices in MD is about 1.2–2.0 times of that in CD. This finding is consistent with the difference of the objective measurement results in different directions of a fabric leading to the diverse subjective evaluation result in human evaluation panels.

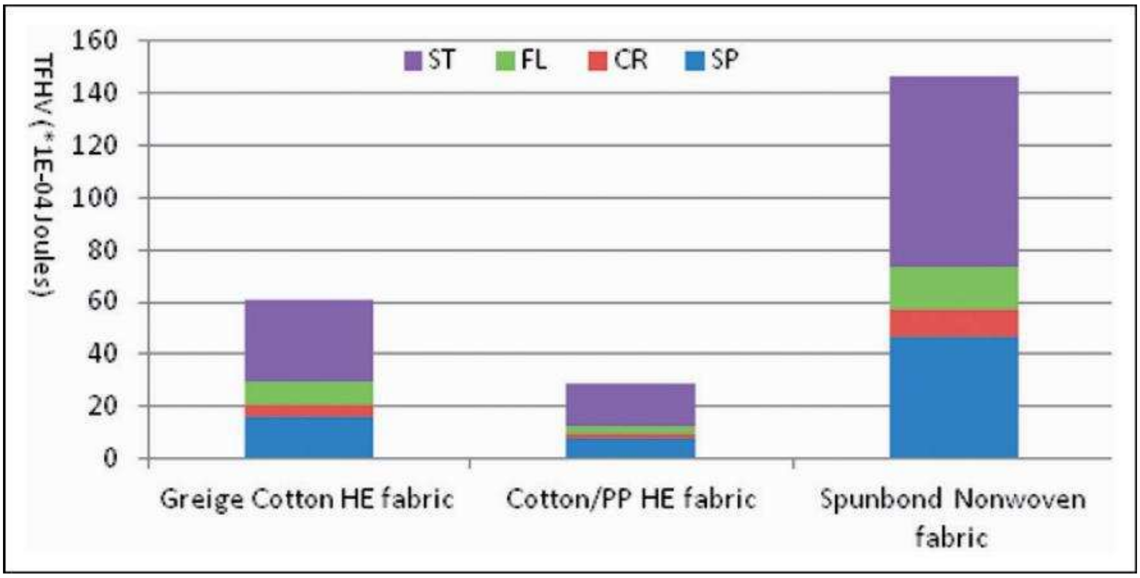

Figure 7. Comparison of total fabric handle value (TFHV) of the three nonwoven fabrics.

As shown in Figure 7 of the three nonwoven fabrics, the 50:50 griege cotton/PP hydroentangled samples was the softest, least elastic, the easiest to dimensionally deform, and the most flexible. It was also found that the PP SM fabric was much less anisotropic than the other two hydroentangled fabrics, and the standard deviation of its indices is the smallest. In contrast, even though the PP SM fabric had the smallest fabric mass per unit area (16 g m^2), it was the least soft, the most resistant to dimensional change, the spongiest, smoothest, and stiffest fabric. The TFHV of the PP SM fabric was about five times greater than that of the 50:50 greige cotton/PP nonwoven fabric and two and a half times that of the 100% greige cotton fabric (see Figure 7).

Conclusions

This study has highlighted the rewet, strikethrough, and fluid acquisition properties of greige cotton nonwovens and contrasted these properties with the previously predicted surface chemistry profile using an electrokinetic model and contact angle measurements. The connection between surface chemistry profiles with the fabric handle model is emphasized in light of the potential topsheet applications of these materials. Studies on how water binds and is held to a partially hydrophobic cotton material and a cotton/PP blend to confer the fluidic and handle properties observed is done by assessing the relative disposition of the hydrophobic versus hydrophilic components. This can be inferred from contact angles that demonstrate a hydrophobic material while providing some wettability. On the other hand, the swell ratio, zeta plateau values, and relative moisture content demonstrate a material where the lower percentage hydrophobic component integrates with the larger hydrophilic cellulosic component. Properties observed with both the fabric fluidic and handle functionalities are consistent with a globally complex water of hydration. It is important to note that the material properties that influence fabric fluidic and handle function are not necessarily similar and are not completely understood as with better characterized systems as wool fibers.[53] However, these studies demonstrate the potential to develop novel topsheets with high functionality from cotton fiber. Water of hydration is fundamentally associated with activity ranging from the molecular to the sensorial level, and the biophysics of water interface activity between the skin and materials is becoming better understood. However, its relative role in effecting energy of deformation pivotal to the LUFHES measurements is not as well understood. Nonetheless, both functional incontinence and handle properties can be better understood by developing a composite water binding model associated with the material properties. This study shows how contact angle and electrokinetic parameters can be helpful in visualizing surface chemistry interactions that collectively form functionality in a novel topsheet design utilizing unsecured cotton similar to polypropylene topsheets. Future studies will focus on examining the fabric handle properties under different moisture levels native to the micro-climate of the skin with nonwoven greige cotton top-sheet motifs.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Wakelyn PJ, Bertoniere NR, French AD, et al. Cotton fiber chemistry and technology. Boca Raton, FL: CRC Press, 2007, p.176.
2. French A, Concha M, Dowd M, et al. Electron (charge) density studies of cellulose models. Cellulose 2014; 21: 1051 – 1063.
3. French AD. Cellulose. In: GCK Roberts (ed.) Encyclopedia of biophysics. New York, NY: Springer, 2013.
4. INDA. Global spunlaced technology market and trends 2011 – 2016. Cary, NC: INDA, 2012.
5. Luitel K, Hudson D and Ethridge D. Evaluating potential for cotton utilization in alternative nonwoven textile technologies. In: Southern agricultural economics association (SAEA) annual meeting, Orlando, Florida, 3 – 5 February 2013.

6. Sawhney APS, Condon B, Reynolds M, et al. Advent of greige cotton non-wovens made using a hydro-entanglement process. Textil Res J 2010; 80: 1540 – 1549.

7. Condon B, Gary L, Sawhney APS, et al. Properties of nonwoven fabrics made with ultraclean cotton. World J Eng 2010; 7: 180 – 184.

8. Sawhney P, Allen C, Reynolds M, et al. Effect of water pressure on absorbency of hydroentangled greige cotton non-woven fabrics. Textil Res J 2012; 82: 21 – 26.

9. Enomae T, Asakawa R, Onabe F, et al. Development of nursing care sheets of cellulosic nonwoven fabrics for aging society. Textil Res J 2006; 76: 41 – 48.

10. Hong KH, Kim SC, Kang TJ, et al. Effect of abrasion and absorbed water on the handle of nonwovens for disposable diapers. Textil Res J 2005; 75: 544 – 550.

11. Brazzini B, Ghersetich I, Hercogova J, et al. The neuroimmuno-cutaneous-endocrine network: relationship between mind and skin. Dermatolo Ther 2003; 16: 123 – 131.

12. Runeman B. Skin interaction with absorbent hygiene products. Clin Dermatol 2008; 26: 45 – 51.

13. Zhong W, Xing MM, Pan N, et al. Textiles and human skin, microclimate, cutaneous reactions: an overview. Cutan Ocul Toxicol 2006; 25: 23 – 39.

14. Cottenden AM, Cottenden DJ, Karavokiros S, et al. Development and experimental validation of a mathematical model for friction between fabrics and a volar forearm phantom. Proc IMechE, Part H: J Engineering in Medicine 2008; 222: 1097 – 1106.

15. Derler S and Gerhardt LC. Tribology of skin: review and analysis of experimental results for the friction coefficient of human skin. Tribol Lett 2012; 45: 1 – 27.

16. Gerhardt LC, Mattle N, Schrade GU, et al. Study of skin-fabric interactions of relevance to decubitus: friction and contact-pressure measurements. Skin Res Technol 2008; 14: 77 – 88.

17. Gerhardt LC, Strassle V, Lenz A, et al. Influence of epidermal hydration on the friction of human skin against textiles. J R Soc Interface 2008; 5: 1317 – 1328.

18. Pan N. Quantification and evaluation of human tactile sense towards fabrics. Int. J Des Nat 2007; 1: 48 – 60.

19. Kawabata S. The standardization and analysis of hand evaluation. 2nd ed. Osaka, Japan: The Hand Evaluation and Standardization Committee, The Textile Machinery Society of Japan, 1980, p.96.

20. Yaman N, S, enol FM and Gurkan P. Applying artificial neural networks to total hand evaluation of disposable diapers. J Eng Fibers Fabr 2011; 6: 38.

21. Bishop DP. Fabrics: sensory and mechanical properties. Textil Progr 1996; 26: 1 – 62.

22. Mao N. Towards objective discrimination & evaluation of fabric tactile properties: quantification of biaxial fabric deformations by using energy methods. In: Proceedings of 14th AUTEX world textile conference, Bursa, Turkey, 26 – 28 May 2014.

23. Anonymous. Phabrometer [06/01/2015]. Available from: http://www.phabrometer.com.

24. Anonymous. Wool handlemeter 2015, http:// www.woolcomfortandhandle.com/index.php/woolhandlemeter (accessed 6 January 2015).

25. Hu J. Characterization of sensory comfort of apparel products. PhD thesis, Hong Kong, Hong Kong Polytechnic University, 2006.

26. Annoymous. Fabric touch tester, www.rycobel.be/ content-downloads/SDL_FTT_PDF_Ryco.pdf (06 January 2015).

27. Liao X, Li Y, Hu J, et al. A simultaneous measurement method to characterize touch properties of textile materials. Fibers Polym 2014; 15: 1548 – 1559.

28. Taieb AH, Msahli S and Sakli F. A new approach for optimizing mechanical clothing tactile comfort. J Adv Res Mech Eng 2010; 1: 43 – 51.

29. Mao N and Taylor M. Evaluation apparatus and method. Geneva, Switzerland: WIPO patent, WO2012104627, 2012.

30. Beguin AM, Malaquin-Pavan E, Guihaire C, et al. Improving diaper design to address incontinence associated dermatitis. BMC Geriatr 2010; 10: 1 – 10.

31. Wu P, Fisher AC, Foo PP, et al. In vitro assessment of water vapour transmission of synthetic wound dressings. Biomaterials 1995; 16: 171 – 175.

32. Edwards V, Condon B, Sawhney P, et al. Electrokinetic analysis of hydroentangled greige cotton – synthetic

fiber blends for absorbent technologies. Textil Res J 2013; 83: 1949 – 1960.

33. Edwards JV, Prevost N, Condon B, et al. Electrokinetic properties of functional layers in absorbent incontinence nonwoven products. Textil Res J 2012; 82: 1001 – 1013.

34. Wenzel RN. Resistance of solid surfaces to wetting by water. Ind Eng Chem 1936; 28: 988 – 994.

35. Cassie ABD and Baxter S. Wettability of porous surfaces. Trans Faraday Soc 1944; 40: 546 – 551.

36. Rowland SP. Cellulose: pores, internal surfaces, and the water interface. In: Arthur JC (ed.) Textile and paper chemistry and technology. ACS symposium series. vol. 49, Washington, DC: American Chemical Society, 1977, pp.20 – 45.

37. Taylor RE, French AD, Gamble GR, et al. 1H and 13C solid-state NMR of Gossypium barbadense (Pima) cotton. J Mol Struct 2008; 878: 177 – 184.

38. French AD, Goynes WR, Rousselle MA, et al. Cotton fiber and moisture – some of the basics. In: Beltwide cotton conferences, 2004, pp.2990 – 2994. San Antonio, TX: Cotton Foundation.

39. Nishiyama Y, Johnson G and French A. Diffraction from nonperiodic models of cellulose crystals. Cellulose 2012; 19: 319 – 336.

40. Venkatraman P, Ashbaugh H, Johnson GP, et al. Simulation studies of the wetting of crystalline faces of cotton cellulose. In: Beltwide cotton conferences, 2010, New Orleans, LA, pp.1577 – 1580.

41. Hermans PH. Contribution to the physics of cellulose fibres. Amsterdam, NY: Elsevier, 1946.

42. Magne FC, Portas HJ and Wakeham H. A calorimetric investigation of moisture in textile fibers. J Am Chem Soc 1947; 69: 1896 – 1902.

43. Magne F and Skau EL. Nonfreezing water and nonfreezing benzene capacities of cottons and modified cottons. Textil Res J 1952; 22: 748 – 756.

44. Stawski D and Bellmann C. Electrokinetic properties of polypropylene textile fabrics containing deposited layers of polyelectrolytes. Colloids Surf A: Physicochem Eng Aspect 2009; 345: 191 – 194.

45. Owens TL. Engineering amphiphilic fabrics for microfluidic applications. PhD Thesis, Georgia Institute of Technology, Atlanta, USA, 2011.

46. Gupta BS. Fluid imbibitions behavior of nonwovens containing cellulose acetate and it blends with synthetic and other cellulosic fibers. In: Proceedings of the belt-wide cotton conferences, 2000, pp.764 – 772.

47. Gupta BS and Hong CJ. Changes in web dimensions during fluid uptake and the impact of absorbency. Tappi J 1994; 77: 181 – 188.

48. Richer C. Trends in disposable diaper design. Ramsey, New Jersey: Nonwovens Industry, 2011.

49. Amidon G and Houghton M. The effect of moisture on the mechanical and powder flow properties of micro-crystalline cellulose. Pharm Res 1995; 12: 923 – 929.

50. Bruno L, Kasapis S and Heng PW. Effect of hydration on the structure of non aqueous ethyl cellulose/propylene glycol dicaprylate gels. Int J Biol Macromol 2012; 50: 385 – 392.

51. Kistamah N and Hes L. Effect of anti-felting treatment on thermal comfort properties of selected wool fabrics in wet state. J Fiber Bioeng Informat 2013; 6: 293 – 300.

52. Kim HS and Pourdeyhimi B. Anisotropy in the mechanical properties of thermally spot-bonded nonwovens: experimental observations. Textil Res J 2001; 71: 965 – 976.

53. Klevaityte R and Masteikaite V. Anisotropy of woven fabric deformation after stretching. Fibres & Textiles in Eastern Europe 2008; 16: 52 – 56.