ABSTRACT

GAHIDE, SEVERINE FRANCOISE. Combination of Hydroentanglement and Foam Bonding Technologies for Wood Pulp and Polyester Fibers in Wet Lay Nonwoven Fabrics.

This project searches for synergism between two binder technologies, specifically 1) low levels of hydroentanglement energy which avoid excessive fiber loss but do not give adequate fabric strength, abrasion resistance or strain recovery, and 2) low levels of binder which do not degrade fabric aesthetics.

The main steps were to 1) determine the fiber loss while hydroentangling, by testing three fabric weights and several specific energy levels for a 50% wood pulp and 50% polyester, and then 2) combine both technologies, for two fiber blends, at three levels of specific energy and four levels of binder add on.

We found that:

1. The carrier screen mesh size, during hydroentanglement, was a critical factor for making the desired fabrics.

2. The fiber loss during hydroentanglement increases linearly with increasing specific energy, in the range studied.

3. The fabric basis weight has a very weak influence on the fiber loss during hydroentanglement.

4. Fabrics hydroentangled from one side only or on both sides lose the same amount of fibers.

5. The physical properties -strength, load at 5% strain, abrasion resistance- are greatly improved with an add-on of binder, while different levels of hydroentanglement energy input were found to be less significant.

6. The hydroentangled and foam bonded fabrics are softer than those which were foam bonded only.

7. The addition of foam bonding up to 5% did not affect the softness of the hydroentangled fabrics.

8. The hydrogen bonding effect is shown to be significant at these levels of hydroentanglement and binder add-on.

9. The fabric bending rigidity can be correlated with the Young's modulus of the bonded fabric for a 60% wood pulp fabric.

10. The abrasion resistance behavior is very different depending on the side tested: foam free or foamed.

COMBINATION OF HYDROENTANGLEMENT AND FOAM BONDING TECHNOLOGIES FOR WOOD PULP AND POLYESTER FIBERS IN WET LAY NONWOVEN FABRICS

by

SEVERINE GAHIDE

A thesis submitted to the graduate faculty
of North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

TEXTILE MANAGEMENT TECHNOLOGY

Raleigh
1999

APPROVED BY

Chair of Advisory Committee

Co-Chair of Advisory Committee

Member of Advisory Committee

BIOGRAPHY

Severine Gahide, daughter of Francoise Torres and Francois Gahide was born in the French Caribbean Islands, on April 10, 1973. She spent most of her life in France, in La Baule where she graduated from high school before she went to study at the School of Textiles Engineering (ESTIT) in Lille (France). She received her Bachelor of Science in Textile and Engineering with a minor in management in May 1997 after spending her senior year, at North Carolina State University, College of Textiles, as an exchange student.

She had the opportunity to work in industry as an intern in France and in the US:

- Bonduel, France (Summer 95) a denim company: Making fabric swatches.
- SMA, France (Summer 96) apparel factory: Process improvement
- Milliken, SC (Summer 97) dyeing and finishing plant: Group coordinator for quality process improvement under the Summer Challenge program
- Swift Denim, NC (August 97) a denim company: Consulting on Total Quality Management

More recently, she was offered a teaching and research assistantship, by the Nonwovens Cooperative Research Center, while completing her MS in Textile Management and Technology, at North Carolina State University. She plans to continue her education towards a Doctorate of Philosophy, in Fiber and Polymer Science, at North Carolina State University.

ACKNOWLEDGMENTS

Nothing would have begun without Raoul. I would like to express my sincere thank to Raoul Farer, doctoral student in Fiber and Polymer Science, at NCSU. He helped me in many ways and he was an example for me. More than a friend, he had the greatest influence on my professional as well as personal growing up. Thank you for this gift.

It would not be fair to forget all the people from the Nonwoven Cooperative Research Center, my sponsor, who made this project more than a reality, a success:

> Dr. Don Shiffler, my advisor, for his wise guidance all along these months,
> Dr. Subhash Batra, director of the research center, for his constant availability,
> as well as Ms. Janey Bullock, our secretary and Mr. Mac McLean, our technician, the two closest persons for my everyday fights.

I also had a great support from the industry, especially, from Ms. Michele Mlynar, of Rohm and Haas, who kindly supplied the necessary binders and Mr. Ron Iff, of Weyerhaeuser, who provided the wood pulp.

Specials thanks go to Dr. David Dickey who has the special gift to make statistics look simple.

Finally, I would like to take this opportunity to thank my parents and my friends, Guillaume, Dr. Jon Rust, Eunice, Ina, Stephan, Sophie and Lee who helped me to keep it cool and fun. Thanks y'all! Merci beaucoup!

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

MD: Machine Direction

CD: Cross Direction

SE: Specific Energy

H/E: Hydroentanglement

1 OBJECTIVES

This research had two main objectives: 1) to quantify fiber loss during hydroentanglement, 2) to find if there was technical merit in using two bonding technologies. The first set of experiments had three specific objectives:

- To identify fiber loss for a 50% polyester 50% wood pulp blend at different levels of specific energy, and for different fabric basis weights.
- To reduce the number of independent variables for the next experiments.
- To find optimum running conditions to combine both bonding technologies while minimizing fiber loss.

The second set of experiments had the following specific objectives:

- To quantify physical properties- strength, elongation, load at 5% strain, and abrasion resistance- when two bonding techniques are combined.
- To estimate softness through bending rigidity measurement.
- To assess available property balances.

2 INTRODUCTION

Nonwovens are defined as sheet or web structures made of randomly dispersed fibers or filaments, excluding paper, that are bonded or entangled by mechanical, thermal or chemical means, and may be modified by additional chemical treatments referred to as finishing. These three steps are commonly named: 1) web formation, 2) web bonding and, 3) web finishing.

Different machines and processes are available to produce a variety of nonwoven fabrics. This diversity gives a whole range of properties and each brings its set of strengths and weaknesses. This literature review focuses on two of these processes: hydroentanglement and foam bonding.

A web can be formed in 4 different ways [1,2]:

- Air lay machines use air turbulence to randomly disperse the fibers.
- Cards use combs and therefore fibers are mostly orientated in the machine direction.
- Wet lay machines use fiber dispersion in water to lay the fibers down on a screen forming a web.
- Meltblowing and spin bonding machines melt and extrude polymers, in the form of fibers, which are blown onto a wire.

Newly formed webs lack cohesion and would fall apart without further treatment. There are several ways to achieve fiber cohesion [2]:

- Chemical adhesives, or resin binders, are padded, sprayed, or foamed into the web, and then cured in an oven.
- Thermoplastic powders can be distributed in the web and then, melt when heated, fusing the fibers to each other.
- Needle punching is a mechanical way of entangling fibers in the web. Barbed needles go up and down through the web while the web is moving. Fibers are entangled while friction between fibers increases, giving a better integrity to the fabric.
- Hydroentangling or spunlacing is alleged to be similar to needle punching. It uses fine high velocity water jets instead of needles.

Post treatments, or fabric finishing, modify final fabric properties such as, aesthetics, drape, softness, strength, color, wettability, or repellency. These additives are padded, sprayed or foamed onto the surface of the fabric. Some of these features can be previously added to the fiber during its manufacture or to the web bonding.

The objective of this research is to combine two bonding technologies: hydroentangling and foam bonding. Both methods have their strengths and weaknesses. We are searching for optimum conditions, which enhance the strengths and minimize, or even eliminate the weaknesses. Section 3.1 will describe hydroentangling technology while section 3.2 will review foam-bonding principles.

3 LITERATURE REVIEW

3.1 HYDROENTANGLEMENT

It all started in 1958 with the first patent granted to Chicopee, followed by the research disclosure, in 1975, done by DuPont leading to Sontara® product [3]. The real take off was to wait until the mid 80's with a medical fabric made by DuPont: Fabric 450®.

3.1.1 Definition

Hydroentangling, or spunlacing, is bonding a web of fibers lying on a conveyor belt using fine, high-pressure speed jets of water. The fibers are pushed through the thickness of the web and turbulence inside the web create entanglement and increases fiber-to-fiber interaction. The jets, after passing through the sheet, rebound from the threads of the conveyor belt. This combination of direct and reflected jets creates an intense agitation inside the sheet entangling the fibers [4]. As a result, fibers can be strongly entangled and fabrics have outstanding strength properties.

Figure 1 shows a pilot-scale hydroentanglement machine. The web is moving from front to back on the inclined conveyor. This machine has three manifolds. The pressure on each manifold can be independently controlled.

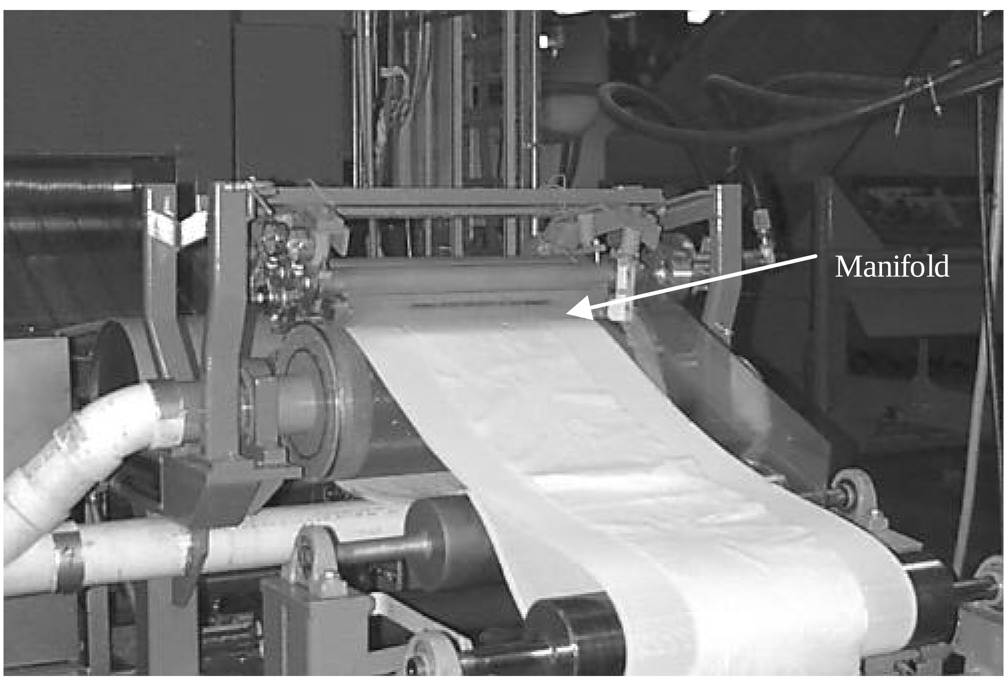

Figure 1: Picture of Honeycomb hydroentanglement machine

Figure 2 is a close up of the manifolds. Inside each manifold, there are one or two lines of jets. The orifice diameter ranges from 0.1 mm to 0.18 mm (4 to 7 mils, 1 mil=1/1000 inch) [1]. The density of jets ranges from 12 to 24 holes per centimeter.

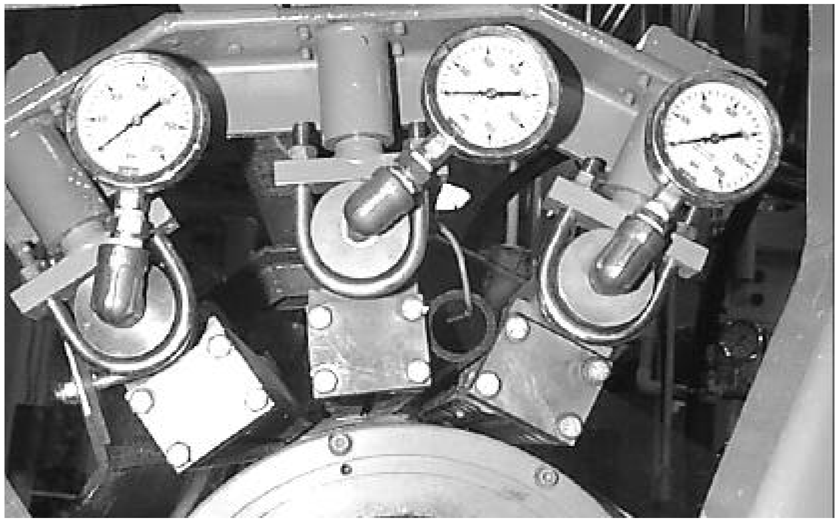

Figure 2: Picture of the manifold

Figure 3 is a schematic side view of the water jets. The pressure behind the jets is as low as 1.38 MPa, or 200 pounds per square inch, for pre-wetting the web, and as high as, 20.7 MPa, or 3,000 pounds per square inch, for high pressure entanglement. In US industry, the pressure is often expressed in pounds per square inch or PSI.

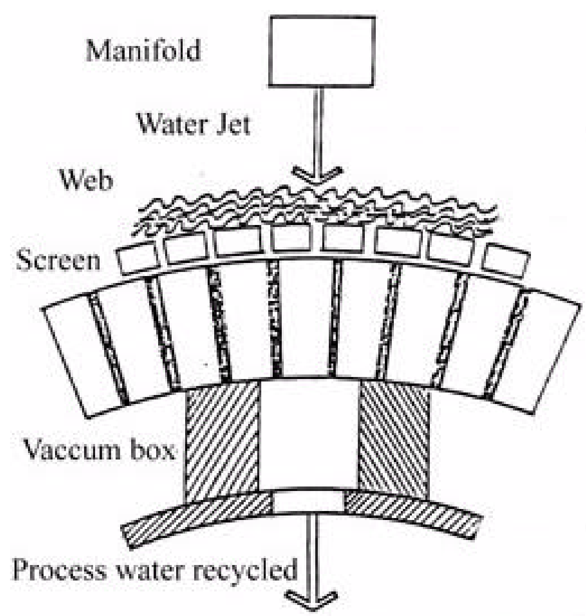

Figure 3: Schematic of a jet [1]: Honeycomb dewatering scheme

3.1.2 Process Variables

Three main critical factors determine the efficiency of bonding.

1- Screen mesh size and type

2- Water pressure in the manifold

3- Specific energy

1- The size of the holes of the conveyor belt screen is a critical factor when hydroentangling. If the holes are too big the smallest fibers will be drained through the screen and raw material will be wasted. If the holes are too small the water will not pass through the screen and will result in unacceptable turbulence at the belt.

2- Water pressure is also a very important parameter. If the water pressure is too low, fibers will not be entangled and therefore the web will not be bonded. If the water pressure is too high, fibers will be washed away and it is impossible to remove the web from the screen.

3- Specific energy is defined as the energy given to the web and largely determines the strength of the fabric. The higher the specific energy, the stronger the web. Gilmore et al [5] calculated the specific energy (SE, hp-hr/lb) as a function of the gage pressure (P, psig) in the manifolds, the number of jets (N) per inch of manifold, the diameter of the orifice (d, in), the coefficient of discharge of the orifice (Cd) assumed constant, the speed of the conveyor belt (S, ft/min), and the fabric basis weight (W, g/m^2). K is a constant obtained using conversion factors and having the value of 17.0 hp-hr-in^2-g-ft/lb$_m$-lb$_f^{3/2}$-m^2-min.

$$SE = (K\,N\,d^2\,C_d\,P^{3/2}) / \,S\,W \qquad (1)$$

Equation (1) is in English units (hp-hr/lb). In this thesis, all units are converted to SI units (kJ/kg) with English units referenced. Specific energy calculations are given in Appendix 1.

Equation (1) is the combination of 1) the nozzle flow (or velocity of the jets) given by Bernoulli's equation and 2) the rate of kinetic energy transfer dE/dt [1].

3.1.3 Hydroentangling technology advances

In 1965, U.S. Pat. No. 3,214,819 defines a method in which water jets are used to provide an entangling action similar to that provided with barbed needles of a mechanical needle loom [6]. Twenty years later, in 1984, E.I. Du Pont de Nemours and Company disclosed an improved liquid-barrier nonwoven fabric made of wood pulp and polyester spunlaced [7]. Closely spaced water jets were used as well as a multiple passes under low pressure in order to ensure these additional properties.

Worldwide production of spunlaced exploded from 40,000 tons in 1987 to 140,000 tons in 1995. Tremendous technological progress was made in less than 6 years [8]:

Table 1: Spunlace technology advances [9]

	1990	Achievable in 1996
Maximum water-jet pressure (bar)	150 (2200 psi)	300 (4400psi)
Basis weight range (g/m^2)	30-200	20-400
Maximum production speed (m/min)	50	300
Energy consumption (KWH/kg)	1.25	0.3
Fiber loss	8%	2%

3.1.4 Advantages and Disadvantages

Advantages and disadvantages of spunlace technology are summarized in Table 2.

Table 2: Hydroentanglement features [1,10,11,12]

STRENGTHS
Very soft fabric
No chemicals
Very flexible
Patterns possible
Low linting

WEAKNESSES
Poor strain recovery
Poor abrasion resistance
Length of fibers critical
Minimum fabric basis weight
High water consumption
Fluid recycle and clogging problem

The most important drawback of spunlacing technology for bonding is the lack of acceptable physical properties in regards to stretch recovery and abrasion resistance of the resulting fabrics. This problem is related to the length of the fibers used. If the fibers are too short, like wood pulp, fibers won't be adequately entangled, and will be flushed through the screen. If the fibers are too long, they will be pushed aside or cut in half and therefore, they won't entangle properly. Short fiber loss is a well-known issue because of recycle filter clogging resulting from that loss. Section 5 of this thesis will study the fiber loss for different basis weights versus specific energy. Another issue is the minimum basis weight for the fabric, empirically known to be around $30g/m^2$. As basis weight decreases the web gets thinner, the number of fibers available to entangle get less and strength decreases to a point where the web cannot be removed from the screen.

The most important advantage of spunlacing technology for bonding is the increase in strength, combined with softness. At high specific energy input, bonds are strong and disentanglement does not occur easily. The growing interest for this technique is caused by the remarkable properties of the product: softness, great patterning possibilities, bacterial barrier effect, very low linting, no chemical bonding agent, drapability, and bulk [10]. Finally, spunlacing is one of the most flexible techniques for bonding since a wide variety of webs can be hydroentangled. Webs can be up to two or three plies that may have different web formation, fiber content, or blend level. This ability of mixing webs and fibers is a unique asset.

Examples of spunlacing products end use are: medical/surgical gowns, drapes, gauze and wipes, also coverstock of diapers, interlining and artificial leather [1].

3.2 Foam bonding

3.2.1 Definitions

A binder is an adhesive (a polymeric compound) applied to the surface of the web. The most important function of binders is to provide integrity and strength to the web by bonding the fibers one to another. Nowadays, they are also to add some specific functions to the fabric, like softness, stretch and recovery, aesthetics (dyeing or printing), or flame retardency, to name only a few [13].

A latex binder is the product of polymerization of monomers and initiators, which is stabilized in water using surfactants [14]. This emulsion contains high molecular weight polymers and has a very low viscosity. The polymer particles surrounded by surfactant molecules are suspended in water and are smaller than 1 micron.

Foam bonding is one of the techniques available for applying a resin binder. A foam is a bubbled structure made by dispersing a gas in a liquid. After being applied to the web, the bubbles break and liquid binder spreads on the fiber surface. The fabric is dried and the curing process occurs.

There are two basic types of foamed latex systems [15]:

1. Collapsible froths
2. Stable foam

A froth is a foam without a foam stabilizer in its formulation. In that case, the bubbles are connected to each other by channels filled with gas [16]. In a foam, each bubble is independent from the neighboring ones, and the ratio of gas to liquid is high. This research used a stable foam.

3.2.2 Chemistry

There are two major binder families commonly used in textiles: 1) acrylics and 2) vinyls. Each family has its set of strengths and weaknesses. The choice of the binder depends upon many considerations but usually the product end use is the leading element in the final choice. The following is an overview of some chemical binder mechanisms. Understanding the chemistry turned out to be fascinating because binders can really be tailored to match the product end use.

The properties of the latex binders are determined by four major elements: 1) the composition of the polymer backbone, 2) the glass transition temperature of the polymer, 3) the functionality of the functional groups, and 4) the additives [13,17].

1- Backbone composition is the monomer chain sequence. Monomers that form the backbone structure play a critical role in the final properties of the binder because they control the glass transition temperature. The chemistry of the polymer chain influences the hydrophobic or hydrophilic character of the fabric, as do the functional groups that are copolymerized.

For example, below is the vinyl monomer unit where R and R' represent various functional groups [14,18].

$$-\left(\begin{array}{cc} H & R \\ | & | \\ C - & C \\ | & | \\ H & R' \end{array}\right)-$$

Vinyl monomer repetition

- If R is H and R'is $OCOCH_3$, then the monomer is vinyl acetate.
- If R is H and R' is C_6H_5, then the monomer is styrene which is hydrophobic.
- If R is H and R' is $CHCH_2$, then the monomer is butadiene which imparts toughness.
- If there is an alternating sequence between a styrene and a butadiene, then the copolymer, often used in nonwovens, is called Styrene Butadiene Rubber or SBR. This compound combines both hydrophobic and toughness characteristics.

- If R' is an organic acid, the monomer is acrylic acid: it is the basis for the family of acrylic monomers. The site R is still available for a family of derivatives.

$$-\left(\begin{array}{cl} H & R \\ | & | \\ C - & C \\ | & | \\ H & COOH \end{array}\right)-$$

Acrylic monomer repetition

By esterifying the organic acid with an alcohol yields a family of acrylate monomers. Acrylate monomers are commonly used in nonwovens because of their ability to add softness and strength to the fabric.

Examples of chemical structures (backbone composition of binders) and their properties [1,13,14]:

- Vinyl acetate is used for its stiffness and low cost.
- Ethylene (a gas at room temperature) copolymerized with vinyl acetate adds softness and flexibility to the copolymer.
- Styrene monomer is hydrophobic and promotes tensile strength.
- Polyvinyl chloride (R is H and R’ is Cl or Chlorine) is a flame retardant.
- Butadiene provides toughness, elasticity and resilience.
- Acrylic copolymers (alkyl acrylate family) have excellent durability to laundering and dry-cleaning due to crosslinkages. They are used extensively in apparel interlinings.

2- Glass transition temperature is the temperature at which the polymer goes from a hard to a soft rubbery behavior. The glass transition temperature, or Tg, is therefore responsible for the hardness or softness of the binder and ultimately the hand of the fabric. Below Tg the material is glassy and rigid [13].

Table 3: Glass transition temperature, Tg, of monomers commonly used in textiles [1,14,19]

Homopolymer	**Tg (^{O}C)**
Ethylene	-93
Butyl acrylate	-54
Ethyl acrylate	-24
Vinyl acetate	+29
Styrene	+100

For textile use, a binder with a Tg below -10 ^{O}C is considered as fairly soft. Tg alone doesn’t predict accurately what the final handle of the fabric will be, because surfactants, added in the latex formulation, will also modify the final hand [19].

3- Functionality is the ability to link some sites to the backbone chain so that special properties are given to the final fabric. Small amounts of monomers are copolymerized onto the backbone chain adding some functionality to the binder.

Note that the backbone composition controls dry properties such as tensile strength, while functionality influences wet properties [13]. For example: if the side-chain monomers are carboxyl or amide groups, the binder self-crosslinks giving strength and toughness to the fabric. Carboxyl groups also increase hydrophilic properties.

As seen before, styrene monomer gives hydrophobic character to the fabric. Adding a carboxyl group to a styrene monomer would not make any sense since it increases hydrophilic properties. The functional group adds, enhances, or increases some existing properties. The choice of the functional groups has to be relevant and should interact with the final desired product end use.

4- Additives are diverse and are used in association with the latex to enhance fabric features such as anti-microbial action, germicidal activity, softness, fluid repellency, color, optical brightness, lubricants (sewing aid) or static dissipation. Most of the time, additives that stabilize foams are added to the formulation, as well as wetting agents to improve the padding process, or the penetration of the foam onto the fabric.

Finally, it is useful to note that what is an asset for one application is a drawback for another. Hydrophilic properties can be enhanced if needed, but are unnecessary for water-repellent fabrics. Stiffness may be critical for a geotextile application but is irrelevant for a surgical gown. End use performance should guide binder selection since binders can be engineered and tailored according to customer requirements [18].

3.2.3 Foam Bonding process

There are 4 ways of applying binders [2,14]:

1- Saturation technique: the web is dipped into the latex and then the excess is removed.

2- Spray application

3- Screen printing, or print bonding: the latex is applied locally in a specific pattern

4- Foamed application

This research focuses on foam bonding. Section 3.5 describes the advantages and disadvantages of the foam bonding process, and shows how hydroentanglement and foam bonding are complementary.

To produce a foam, the liquid binder has to be mixed with air. By producing bubbles, the interface liquid/air surface area increases tremendously. The free energy is the work necessary to create surface area and is expressed for a liquid interface [20]:

$$\mathbf{DF = s\ (DA)} \qquad (2)$$

Where:

> ΔF: Free energy, dyne-cm
>
> σ: Surface tension of the fluid, dyne/cm
>
> A: Interfacial surface area, cm^2

Therefore, to generate a foam, or increase the liquid-air interfacial area (ΔA), work is required. This work is provided by the foamer (rotating plates or cylinders with teeth) [16] and the blower. To reduce the amount of work required, surfactants are added to the binder mix to lower the surface tension. Coalescence is of lower energy, and explains why the foam is an unstable phase.

Figure 4 is a photograph of a pilot scale foam applicator unit. The web is moving from left to right. When the foam unit is on, the web is squeezed between the white plane surface and the roller. The foam is applied under pressure to the fabric pressed against the rotating cylinder through the white plane surface. The pressure of the jet foam applicator on the fabric maximizes the penetration of the foam into the web.

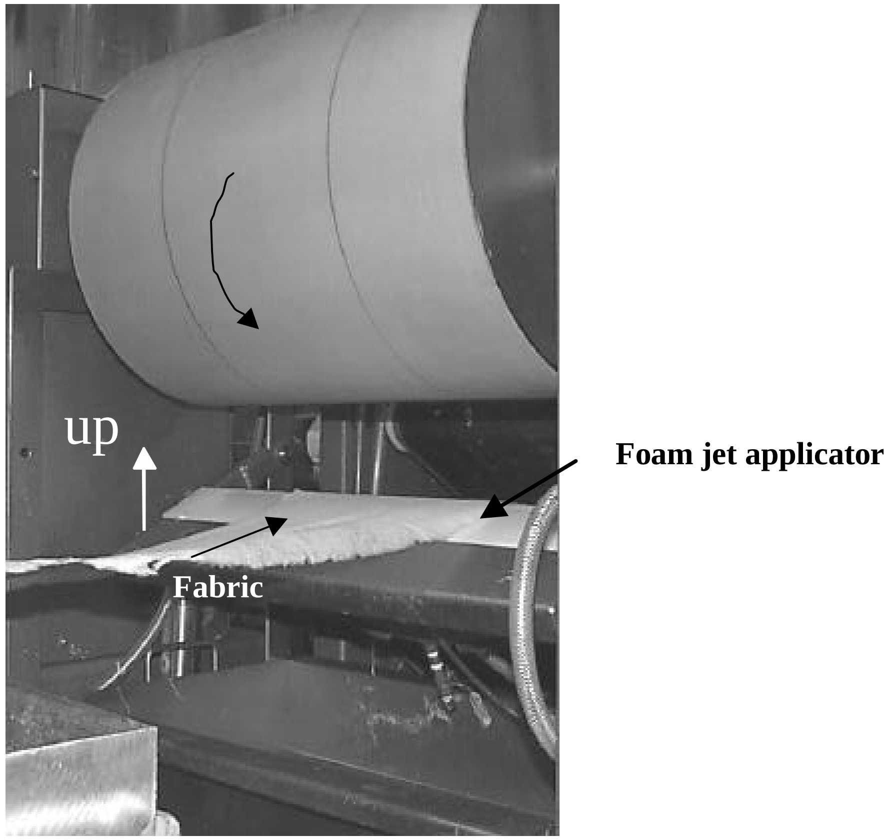

Figure 4: Gaston County Foam Application unit

3.2.4 Process variables

It is very important to have an even distribution of the foam on the web. Several parameters may influence the uniformity of bonding: foam homogeneity, applicator pressure, half-life time of the foam, foam blow ratio, and back pressure.

The foam should be homogeneous and consist of fine bubbles of approximately 0.5 mm in diameter [21]. Bubble size is controlled by the foamer speed. The size of the bubbles decreases and the foam gets stiffer, as speed increases [22].

The foam pressure in the applicator manifold, for the Gaston County laboratory machine, ranges from 2 to 10 inches of water column (0.50 to 2.50 kPa). It is controlled by the clearance between the roll and the applicator plate. If the pressure is too low, a spotty uneven distribution results on the fabric. If the pressure is too high, the foam tends to leak on the sides of the fabric and between the applicator and the fabric [21].

Collapsible foams have limited life times. Half life is used to describe the disintegration rate and is the time required for half the foam to coalesce. In order to have a uniform coverage of binder on the surface of the fabric and an adequate penetration of the binder through it, the foam should not disintegrate too fast [23].

For a batting applicator machine, such as the Gaston County machine, the half life range is from 6 to 20 minutes. At low level of add-on binder foam, half life is a critical variable. If the foam half life is below this range, it coalesces before reaching the applicator. If the half life is above this range, it will not collapse when it touches the fabric. In addition, it may be pushed to the sides and miss the web [22].

Blow ratio is the amount of air to the amount of latex by volume. A common rule of thumb is 8:1 for a simple surface coverage, and 20:1 and over for a full penetration [22]. Problems of foam starvation, or distribution evenness, are solved by increasing the blow ratio but consequently bubble size decreases and viscosity increases, so the back pressure increases and the foam velocity decreases [22].

Back pressure, the pressure at the foamer outlet, is an indication of foam quality in a given system. If the back pressure is too high, the foam is destroyed and tear shape holes appear on the fabric. Back pressure can be lowered by reducing blow ratio, increasing the diameter of the hose between foamer and applicator, or adding some soap to the formulation to decrease the viscosity [22]. The acceptable back pressure, for the laboratory equipment, is 30 to 60 PSI [21].

3.2.5 Advantages and Disadvantages

Advantages and disadvantages of foam bonding technology are summarized in Table 4.

Table 4: Foam bonding features [14,22].

STRENGTHS
Strength increases
Additional properties
Exact amount of binder
Energy saving

WEAKNESSES
Stiffness
Chemical hazard
Toxicity

The biggest problem with foam bonding is the increasing stiffness of the fabric. When the foam is cured, the resin forms a "coat" and the fibers are glued together. The fabric loses its natural softness, even when the add-on is at low level. Another issue is the chemical hazard of the binder [17]. Foam bonding is not suitable for apparel if the latex produces any formaldehyde (commonly contained in textiles surfactant). Binder additives or curing by products can be toxic for humans and therefore may require special care when used.

Despite those disadvantages, foam bonding has been very popular in the nonwoven industry because additional properties such as water repellency, wettability, flame retardency, stain resistance, static dissipation can be added to the fabric. Wet pick up is very low so foam bonding turns out to be cost effective and a more efficient way of applying latex compared to traditional pad dipping processes. Less water and lower drying temperatures are used, and the amount applied is controlled much better [23].

3.2.6 Conclusion

Because of the variety of vinyl monomers, functional groups, and surface active agents available, nonwoven latex binders can be engineered for specific end use applications. They are capable of providing a whole range of additional aesthetics, physical or chemical properties and they are inexpensive.

3.3 Combining spunlacing and foam bonding

In the mid 80's, lightly entangled and dry printed nonwoven fabrics were claimed by Chicopee under the U.S. Patent 4,623,575. The addition of an adhesive binder to the polyester and polyolefin spunlaced fabric resulted in an excellent combination of strength, softness and durability, although in this case the method of bonding was not foam bonding but dry print bonding (the fabric is first prewetted, dried and then the binder is applied) [24].

Recently, U.S. Pat. No. 5,000,747, assigned to Dexter Corporation, describes the combination of hydroentanglement and foam bonding technologies for a wet lay fabric made of wood pulp and polyester [25].

They claim:

- Foam bonding pick up between 3 to 15 percent binder
- Ultra low water jet pressure with a specific energy up to about 0.2 hp-hr/lb
- Binder: crosslinkable acrylic latex dispersion

It was found that the strength increased when a low level of binder add-on is applied.

Our research concentrates on much smaller quantities of binder add-ons: less than 5% and the specific energy input ranging from 0 to 0.61 hp-hr/lb. The chemical binder formulation was different since Rhoplex 1845K is an anionic formaldehyde-free binder.

4 EXPERIMENTAL METHODOLOGY

4.1 FIBERS

Wood pulp (natural cellulose) and polyester manmade fibers were used in this study.

- Wood pulp[1] was chosen because it is an inexpensive material [26]. In addition, wood pulp fibers create hydrogen bonds when dry, have great absorbency properties, and are effective pathogen barriers because of their fibrillate nature.
- Polyester fibers[2] were selected to reinforce the web structure and give more cohesion to the web because of their length, while not creating clumps during the web formation.

Table 5: Fiber properties

Wood pulp	**Polyester**
<3 mm	6.3 mm (1/4 inch)
Pine	1.77 dtex (17.7 g /1000 m) (or 1.5 den)
Dirt:0.36- Brightness:89.5	

4.2 WEB FORMATION

4.2.1 Wet lay process

The wet lay process is a direct development from the paper making industry. Water is used as a means for dispersing the fibers randomly. Figure 5 is a schematic of the wet lay process.

1- Courtesy of Weyerhaeuser Company, Tacoma WA.
2- Courtesy of Hoechst Celanese (Trevira).

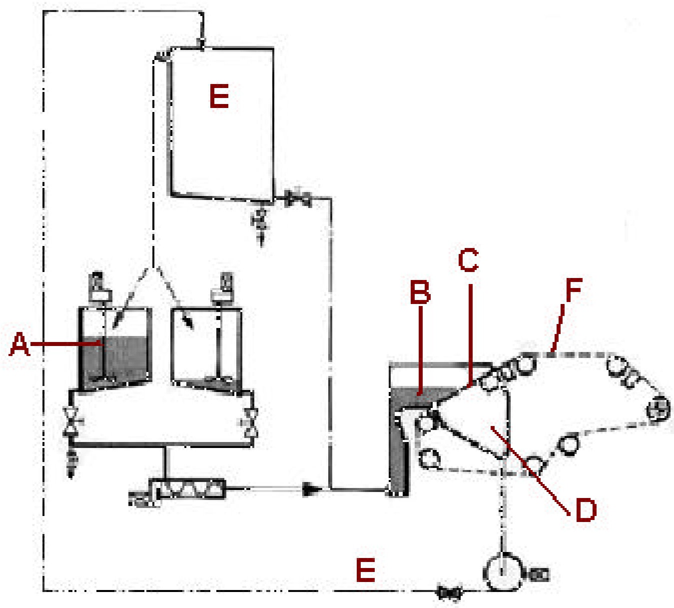

Figure 5: Wet lay process schematic [27]

1- Polyester and wood pulp fibers are poured into the dispersion tank **(A)**, and stirred, in 300 l of water, for 25 minutes. The material concentration is around 0.3% by weight.

2- The slurry (water + fibers) is pumped to the head box **(B)**, and diluted to a concentration of approximately 0.02% by weight.

3- The inclined belt conveyor **(C)**, or wire screen, takes away the fibers, while the water is sucked **(D)** through the screen.

4- The water is then recycled **(E)**, while fibers fall on top of each other forming a "web" **(F)**. At this point of the process, the fibers have little cohesion (water surface tension only) and need to be bonded.

Figure 6 is a picture of the small-scale wet lay pilot machine used for the experiments. It is an inclined wire Foudrinier.

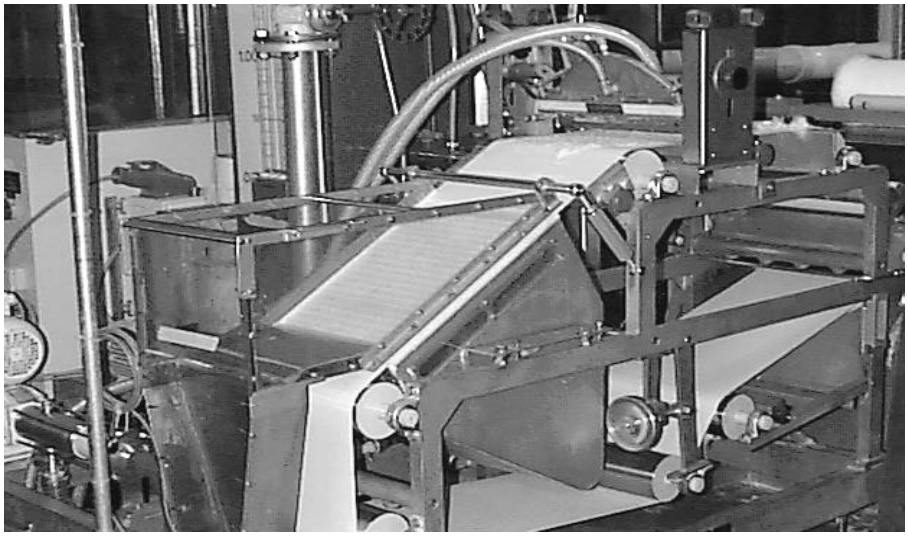

Figure 6: Neue Bruderhaus wet lay machine

4.2.2 Dispersion problems

A critical factor in the wet lay process is dispersion efficiency. If the dispersion were perfect, the basis weight would be constant and the fibers would be homogeneously blended along the web. While 25 minutes dispersion time was found long enough to avoid major defects such as clumps, fabric basis weight was not found constant along the web. Surprisingly, the blend ratio stayed the same.

Figure 7 shows the variation of the fabric basis weight along the length of the web. The target was 50 g/m^2. The web was acceptable for the first 12 meters, but the basis weight dropped down to 28 g/m^2, a 44% variation. The same experiment was repeated 4 times, and showed the same exact decrease after 12 meters. Therefore, only the first 12 meters were used for further experiments. Further work should be done in this area to investigate this unexpected variation.

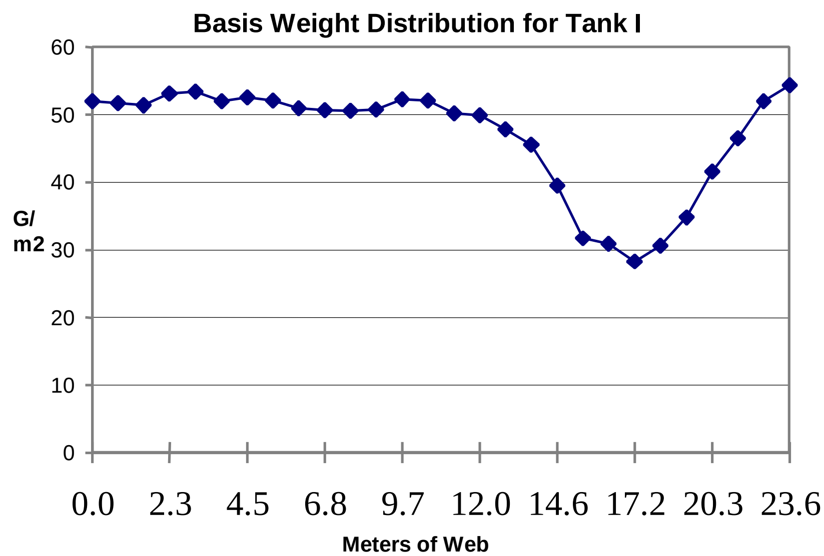

Figure 7: Basis weight variation during web formation

We took 5 samples for the blend content along the web. The samples were extracted in a 65% sulfuric acid solution for 30 minutes to remove the wood pulp. A simple weight comparison was done to determine the blend content. The fabric studied was nominally a 30% wood pulp 70 % polyester. The following table shows the observed blend contents:

Table 6: Wood pulp content vs. web formation

Meter of web formed	% Wood
1	37 %
6	38 %
12	35 %
14	50 %
20	38 %

Since only the first 12 meters were used, because of the basis weight variability, we considered the web to be homogeneously blended, and accepted it.

4.3 DESIGN OF EXPERIMENT

Two experiments were designed. The first assessed fiber loss, the second studied the combination of hydroentanglement and foam bonding.

4.3.1 Fiber loss

The first set of experiments was designed to determine fiber loss during hydroentangling and to select suitable energy levels for the second set of experiments (described in section 4.3.2). Three parameters were considered:

- Fabric basis weight:

  - 60 g/m^2 -100 g/m^2 - 140 g/m^2

- Specific energy levels: from 1400 to 7600 KJ/kg (or 0.24 to 2.0 Hp-hr/lb)
- Hydroentanglement on both sides and on one side only

while other parameters were held constant, such as:

- Fabric blend: 50% Wood pulp - 50% Polyester
- Screen mesh: 100
- Vacuum and drying conditions

Design of Experiment:

Table 7: Design of Experiments

SE (kJ/kg)	1400	1940	2150	3000	3450	4500	4800	7600
SE (Hp-hr/lb)	0.24	0.33	0.36	0.5	0.58	0.84	0.81	1.29
59.4 g/m^2	-	-	-	-	AA AB	-	AB	-
96.1 g/m^2	-	-	AA AB	AB	-	-	-	AB
147.1 g/m^2	AA AB	AB	-	-	-	AB	-	-

AB: Both sides (top side and then bottom side)
AA: Same side twice

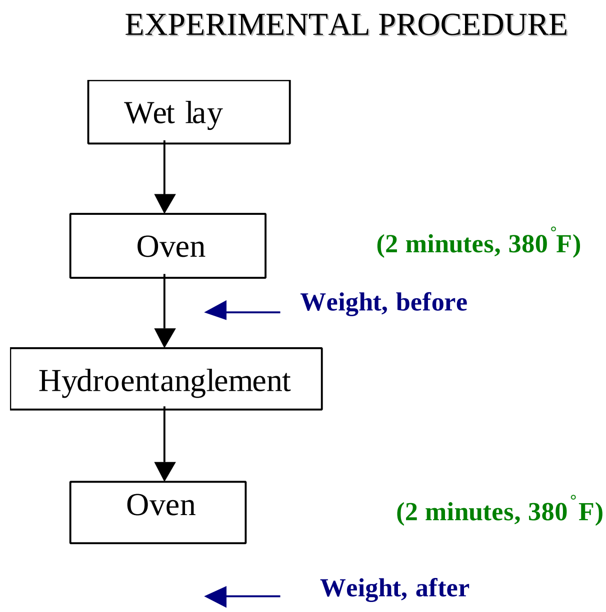

Figure 8: Fabric formation process I

Ten handsheet samples per fabric basis weight and level of specific energy were collected and a full set of replicates for 100 g/m^2 was done.

To compute the loss of short fibers, dried handsheet weights were obtained before and after hydroentanglement and compared.

$$\text{Loss \%} = \frac{\text{Weight before} - \text{Weight after}}{\text{Weight before}} \times 100 \qquad (3)$$

4.3.2 Combination: hydroentanglement and foam bonding

The second set of experiments was to study the combination of the two bonding technologies: hydroentanglement and foam bonding.

Three independent variables were explored:

- Fabric blend:

  - 30% Wood pulp, 70% Polyester
  - 60% Wood pulp, 40% Polyester

- Specific energy level:

  - None
  - 2400 kJ/kg (or 0.40 Hp-hr/lb)
  - 3600 kJ/kg (or 0.61 Hp-hr/lb)

- Foam add-on:

  - 0%
  - 1.25%
  - 2.5%
  - 5%

Other parameters were held constant, such as:

- Fabric basis weight: 50g/m^2
- Hydroentanglement screen mesh: 100
- Binder: NW 1845K[1]
- Vacuum and drying conditions

1- Rhoplex NW 1845 K (provided by Rohm and Haas). Because of its formaldehyde-free properties, this anionic binder is ideal for medical/hospital underpads, drapes, gowns or facemasks. This modified acrylic binder has excellent wet tensile strength, gives a hydrophobic fabric, and a very soft hand (Tg=-21ºC).

EXPERIMENTAL PROCEDURE

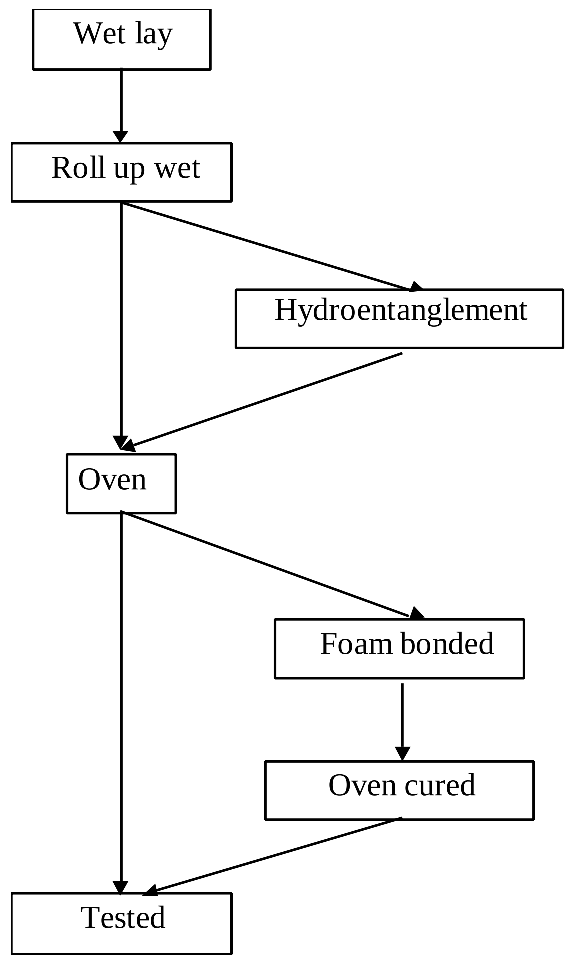

Figure 9: Fabric formation process II

5 STANDARD TESTS

The test methods chosen were those recommended by ASTM D-1117-97: "Standard test methods for nonwoven fabrics" [28]. This is an overall protocol.

5.1 BENDING RIGIDITY

Bending rigidity is a good estimate of the softness of a fabric. The lower the flexural rigidity, the softer the fabric. The method recommended for nonwoven in the ASTM book of tests is the ASTM D-5732-95: "Stiffness of nonwoven fabrics using the cantilever test" [29].

- The sample size is 2.54 cm x 20.32 cm (or 1 x 8 in).
- We tested five samples in the machine direction and eight samples in the cross direction.

Each sample is individually weighted and then slid along the cantilever apparatus, until it starts bending under its own weight. The overhang length is then recorded. The bending rigidity is calculated from the following formula:

$$\mathbf{G= 2.45 \times 10^{14}\ W\ \ (C)^{3}} \qquad (4)$$

Where:

G = Flexural rigidity, Nm

W = Weight of sample, g

C= Bending Length, mm

O = Overlay length, mm

C = O/2

Results are given in Appendix 7.

5.2 TENSILE TEST

The tensile test provides much information: breaking load, the percent elongation at maximum load, the load at 5% strain, and the Young's modulus of the fabric. The test was performed on an Instron 4400R, using the ASTM D-5035-95 (strip method): "Breaking force and elongation of textile fabrics" [30] (formerly ASTM D-1682).

- The sample size was 2.54 cm x 20.32 cm (or 1 x 8 in).
- The gage length was fixed at 76.2 mm (or 3 in).
- The speed of elongation was 300 mm/min (400%/min strain rate).
- Five samples in the machine direction and eight samples in the cross direction were tested.

The sample is clamped in parallel jaws of the tensile testing machine. The jaws are continuously separating until the sample breaks. The loads at 5% and at breakage are recorded, as well as the percent elongation, or percent strain, at breakage. The breaking curves are also available. Results are in Appendices 4,5 and 6.

5.3 Abrasion

Abrasion resistance was measured on a Taber Abrasion Tester according to the ASTM D-3884-92: "Abrasion resistance of textile test" [31].

- The sample size was 12.7cm x 12.7 cm
- The abraders were CS-10, for light fabrics only.
- The weight attached to the abraders was 500g.
- The vacuum level was100 Hg.
- Each fabric was tested 4 times: twice on the side with foam, and twice the side without foam.

The sample is tied up on a rotary surface and the two abraders are on top of the fabric. The abrasion resistance is measured as the number of cycles the fabric withstands before its surface breaks and the surface below the fabric can be seen. Results are in appendix 8.

6 Results and Discussion

6.1 Fiber Loss

6.1.1 Fiber loss experiments

Under the experimental conditions described in 4.3.1 section, we found several interesting results:

Screen mesh size is a critical factor during hydroentanglement while making fabric. First, a 40 x 60 mesh was tried but many fibers were washed out that the web could not be removed from the screen. Next a finer screen, 100 mesh, was used. With a 100 mesh, at 2.0 hp-hr/lb (highest hydroentanglement conditions), the 60g/m^2 web (the lightest web) could not be removed from the hydroentanglement screen because of insufficient bonding. All other samples were bonded adequately.

Figure 10 shows, as expected, that the higher the specific energy, the more fibers are lost. A p-value of 0.0006 shows a very strong relation between specific energy and fiber loss.

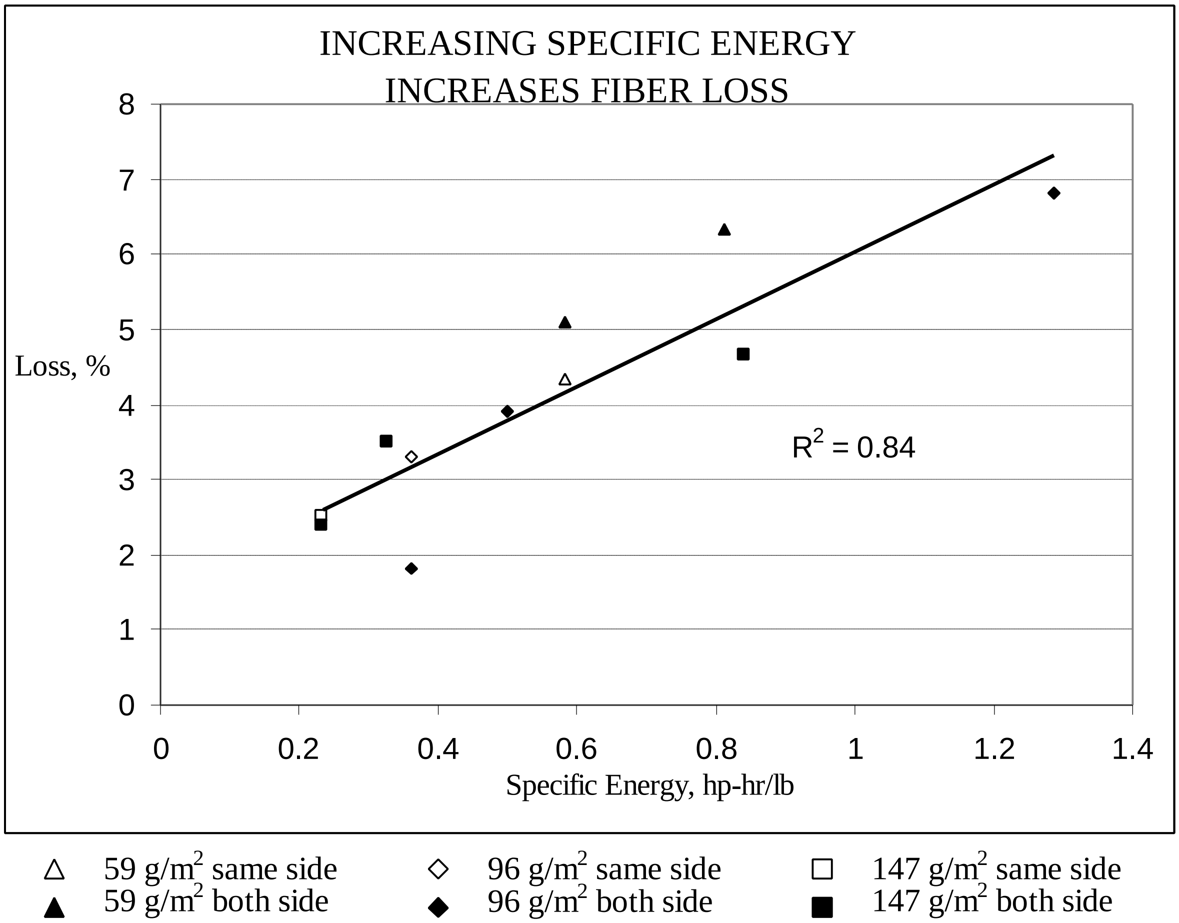

Figure 10: Fiber loss vs. Specific Energy

Each data point on the graph is an arithmetic average of 10 specimens treated alike.

The relation between fabric basis weight and fiber loss is not significant with a p-value of 0.1825. At 5% significance level, we fail to show evidence of a relation between fabric basis weight and fiber loss in the range of 60 g/m^2 to 140 g/m^2 for a 50-50 wood pulp-polyester.

Therefore, the best statistical model to fit fiber loss is a linear model ($R^2 = 0.84$).

$$\textbf{Loss} = \mathbf{2.74 + 4.10\ SE - 0.001\ W} \qquad (5)$$

Where: SE: Specific Energy, hp-hr/lb

W: Fabric basis weight, g/m^2

All data and SAS analysis are shown in Appendix2.

Higher specific energy may require two passes. Therefore, it is important to know if two passes with the same side facing the jets is different from one pass with side A and then second side B on top facing the jets.

Ho: There is no difference between fabrics hydroentangled twice on the same side and fabrics hydroentangled once on both sides.

H1: There is a difference between the two treatments.

$\mathbf{t_{theo} = 4.303 > t_{cal} = 1.30}$ so we cannot reject Ho hypothesis.

We fail to show evidence of differences between the two different treatments at 5% significance level. We conclude that flipping the fabrics when there are several passes won't create a significant error. All data and statistical analysis are in Appendix 3.

No identification of the nature of the fiber lost was done. Furthermore, any weight loss was called fiber loss, but it could also be impurities or surface coating. This would be very true with cotton [5].

6.1.2 Combination of two bonding technologies experiments

Under the experimental conditions described in section 4.3.2, we found that, even at a low level of specific energy, there is still a fiber loss effect. Although we tried to minimize this effect in our design of experiments, Figure 11 illustrates the observed fiber loss.

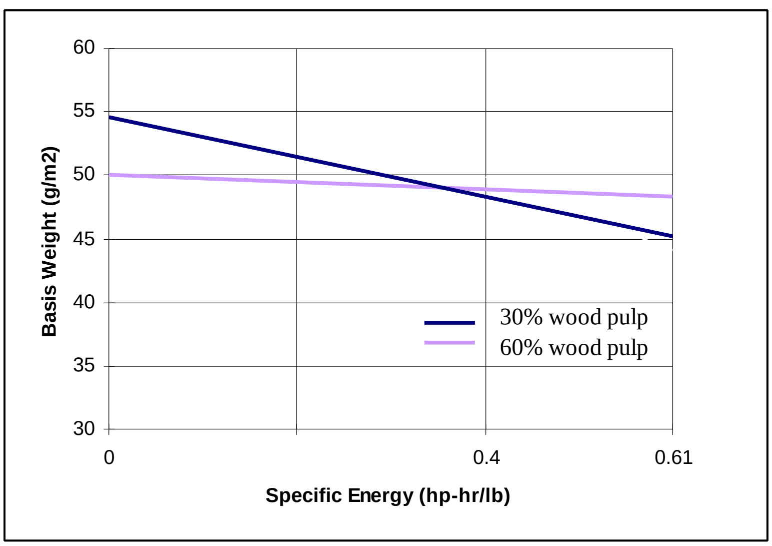

Figure 11: Basis weight vs. Specific energy

Therefore, to compare the different samples to each other, we normalized the fabric basis weight to 50 g/m^2.

Surprisingly, we found that the higher the wood pulp, the less the loss. This appears to be a "filter cake" effect. At 30% wood pulp, the long fibers act as a network. The shorter fibers are drained through the network resulting in the loss of fibers. However, if the amount of short fibers is sufficiently increased, the small fibers bridge the network creating a filter so less short fibers can get through the web.

6.2 COMBINATION OF THE BONDING TECHNOLOGIES

There are three possible bonding effects, under our experimental conditions:

- Hydroentangling effect: fibers are physically entangled
- Foam bonding effect: fibers are "glued" together after being dried.
- Hydrogen bonding effect: wood pulp fibers are bonded through "hydrogen bonds".

6.2.1 Maximum load

Figures 12 and 13 show the normalized data recording the load at break. Data analysis is given in Appendix 4.

HYDROENTANGLEMENT

Hydroentanglement does not explain the changes in strength. We fail, at 5% significance level, to show evidence of an effect of hydroentanglement on strength (p-value = 0.23).

There is no significant difference between low and high hydroentanglement levels (p-value = 0.229). There is no significant difference between hydroentangling or not hydroentangling (p-value = 0.44) at 5% significance level.

Overall, hydroentanglement, at any energy level, is not a significant factor affecting strength (p-value = 0.23 >>0.05). One could expect to find that increasing the specific energy would also increase fabric strength because fiber entanglement increases. However, increasing the specific energy also decreases the number of contacts between fibers because the jets cause bigger open spaces. Less fiber-to-fiber contacts mean a decrease in the hydrogen bonding effect. So these phenomena compete and the net effect is little change in fabric strength. This is the reason why there are not three parallel curves, but only one, when strength is plotted.

Another possible explanation is the fiber length. The longer the fibers, the more contacts and entanglements they can participate in. Wood pulp fibers are considered short fibers with the maximum length less than 3 mm. Therefore, they cannot participate in many entanglements and hydroentanglement bonding is not fully exploited.

FOAM BONDING

There is a strong foam effect (p-value = 0.0001) and strength increases proportionally to the amount of binder add on.

We observe a break in the mechanical properties between having or not having foam –the values at 0 % foam do not fit the trendline, especially for the 30% wood pulp webs. This is the foam effect. The strength increases by four times as soon as some latex is added. Finally, percent binder add-on is the only significant parameter, with a p-value of 0.0001.
We have the false impression that the 60 % wood pulp webs do not follow the same trend and that the values at 0 % foam case fits the trendline. Actually, the same behavior is observed with the 60 % wood pulp, but it is masked by the hydrogen bonding effect. As the wood pulp fiber content increases, more hydrogen bonds are created. Therefore, hydrogen bonds provide more web cohesion and replace the lack of foam.

When all data are combined, regardless of the blend or the direction, an acceptable statistical model is:

Max. load (cN/cm)= 54 + 19 Binder add-on (%) + 31.9 Specific Energy (hp-hr/lb) (6)

with a p-value = 0.0001, and R^2=0.67.

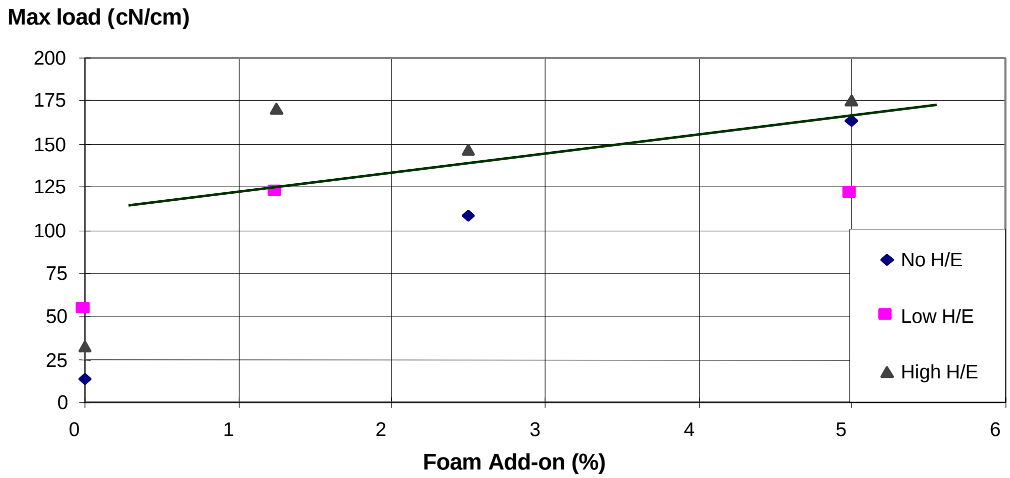

Figure 12: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) tensile strength, for a 30% wood pulp/70% polyester blend.

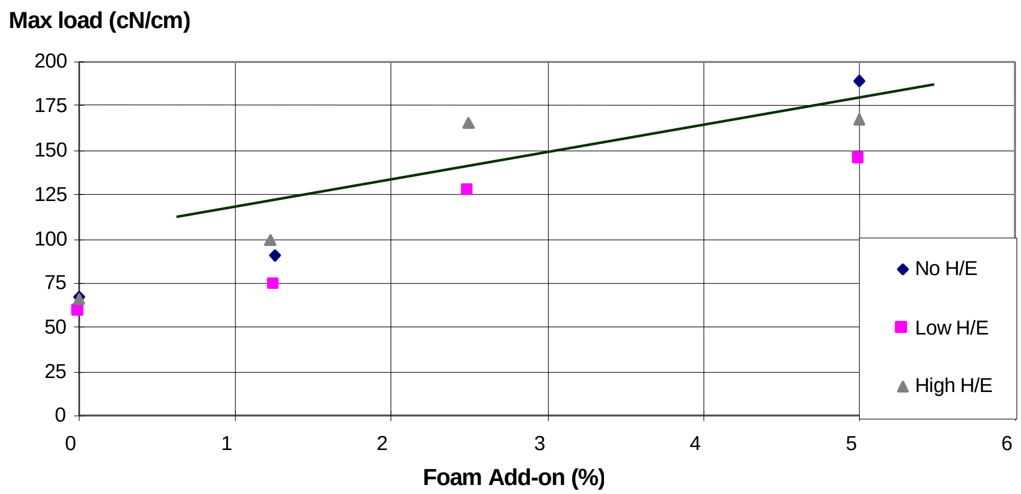

Figure 13: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) tensile strength, for a 60% wood pulp/40% polyester blend.

6.2.2 Elongation at maximum load

There is no need to normalize the data because elongation doesn't depend on the basis weight. Figures 14 and 15 summarize the results.

HYDROENTANGLEMENT

There is a significant hydroentanglement effect on the maximum elongation and a significant difference between hydroentangling and not hydroentangling (p-value = 0.0001), but not between the two levels of specific energy -low and high (p-value = 0.215).

FOAM BONDING

There is a foam bonding effect on maximum elongation. The influence of level binder add-on is found to be statistically significant (p-value = 0.0003).

The statistics above are given for all data, regardless of the blend, because both blends showed the same behavior and were not statistically different (p-value=0.79). All data are shown in Appendix 5.

When the values are averaged over blends and directions, the statistical model that best fits is a linear model with $R^2 = 0.87$.

Percent Elongation = 2.117 + 0.937 Binder add-on (%) + 17.106 Specific energy (hp-hr/lb.) (7)

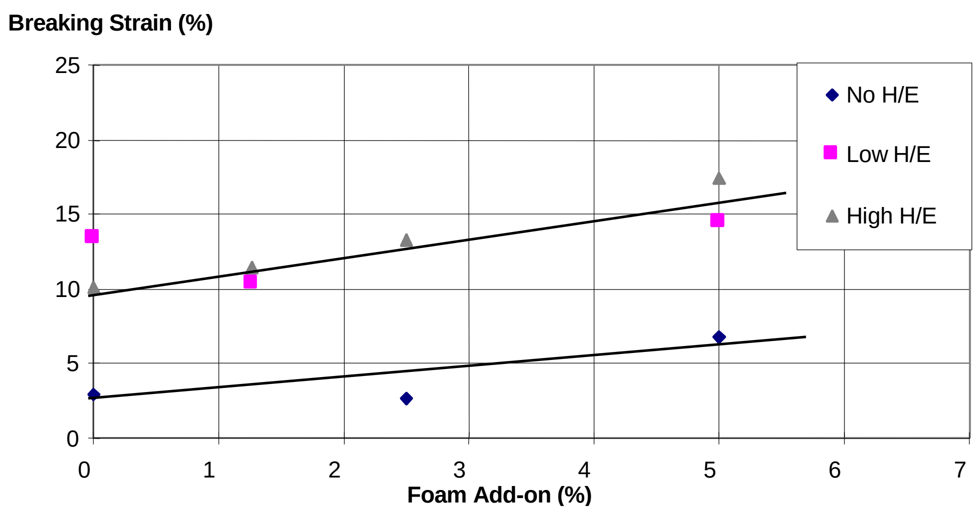

Figure 14: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) breaking strain, for a 30% wood pulp / 70% polyester blend.

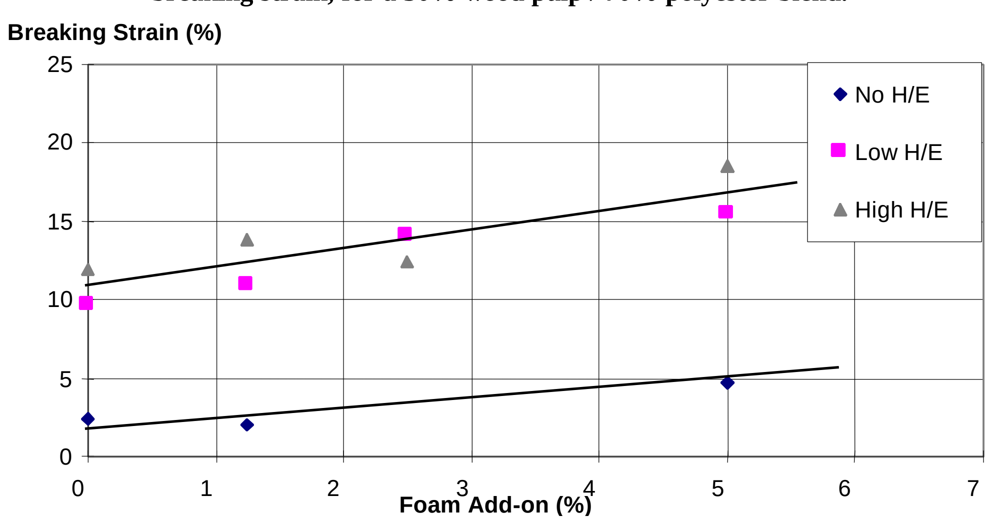

Figure 15: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) breaking strain, for a 60% wood pulp / 40% polyester blend.

6.2.3 Load at 5% Strain

The load at 5% strain gives a real feeling of the strength of the fabric because it represents the value under normal use of the fabric, not under the extreme conditions at the break. There are no conclusive results for the webs with 30% wood pulp content, which have not been hydroentangled, at low level of binder, because they break at less then 5% strain. To cancel the fiber loss effect, as a source of variability, we normalized the fabric basis weight to 50 g/m^2. Tensile strength and basis weight are directly related. Figures 16 and 17 show the results.

HYDROENTANGLEMENT

There is no hydroentanglement effect. We fail, at 5% significance level, to show evidence of an effect of hydroentanglement on the load at 5% strain (p-value = 0.97).

There is no significant difference between low and high hydroentanglement levels (p-value = 0.29). There is no significant difference between hydroentangling or not hydroentangling (p-value = 0.45).

FOAM BONDING

There is a strong foam bonding effect (p-value = 0.0001), even if it is masked by hydrogen bonding for the webs at 60% wood pulp content.

Strength, as define above, increases proportionally to the amount of binder add on (p-value = 0.0005).

The tensile strength curves at maximum break (showed in Figures 12 and 13) have exactly the same trends as the tensile strength curves at 5 % load. Therefore, we can assume the physical behaviors follow the same explanations (See paragraph 6.2.1). Notice that for the 60% wood pulp fabric, the best statistical model is a straight line with $R^2 = 0.834$. This r-square does not include the values at 0% foam because, as already pointed out, there is a special mechanical behavior under this condition. See Appendix 6 for details.

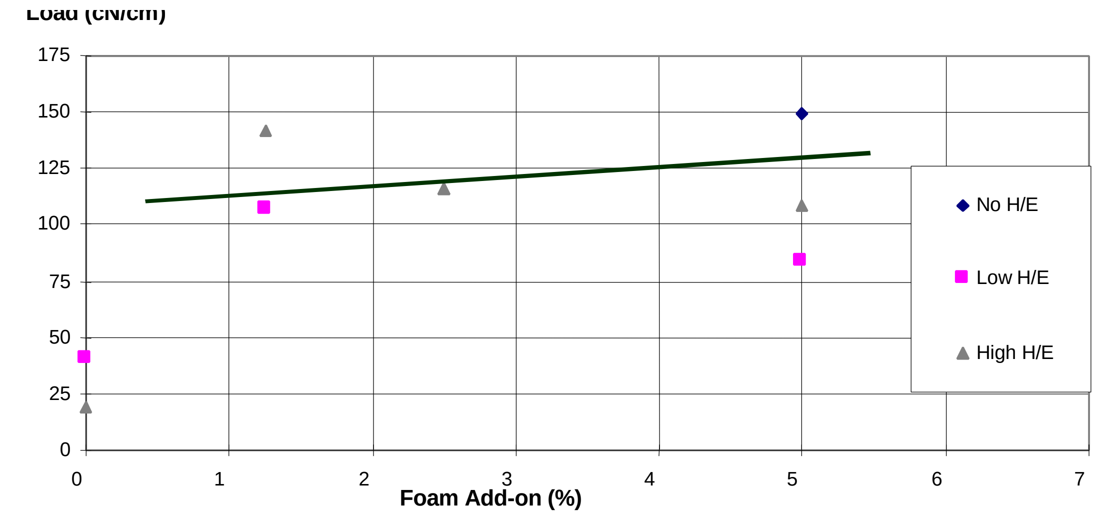

Figure 16: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) of the load at 5% strain, for a 30% wood pulp / 70% polyester blend.

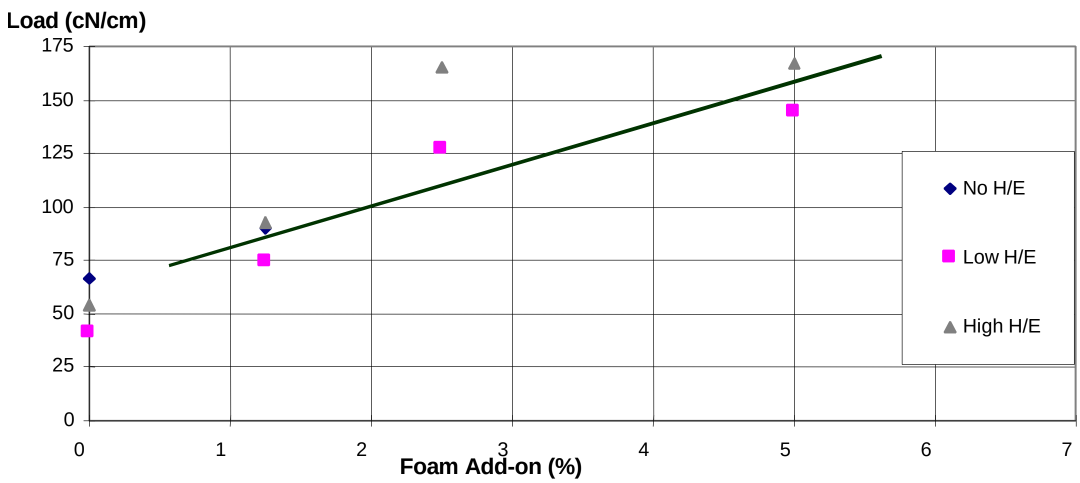

Figure 17: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) of the load at 5% strain, for a 60% wood pulp / 40% polyester blend.

6.2.4 Bending rigidity

Bending rigidity is one of the contributors to the softness of a fabric. The lower the flexural rigidity, the softer the fabric is likely to be. In this regard, the two blends, in the present case, behave very differently, as illustrated in Figures 18 and 19.

For a 30% wood pulp fabric:

HYDROENTANGLEMENT

Figure 18 shows that the stiffest webs are the non-hydroentangled ones. However, this observation is not statistically significant (p-value = 0.1687). The same graph also shows it is necessary to optimize specific energy to preserve softness. Again, it is not statistically significant. There is no difference between low and high levels of hydroentanglement (p-value = 0.763).

The fabrics that are not hydroentangled feel paperlike. Therefore, hydroentanglement does improve softness even if not detected by bending rigidity measurements. There is an optimal specific energy input beyond which more fibers are lost and the fabric gets stiffer.

FOAM BONDING

There is no detectable foam bonding effect on bending rigidity (p-value = 0.942>>0.05).

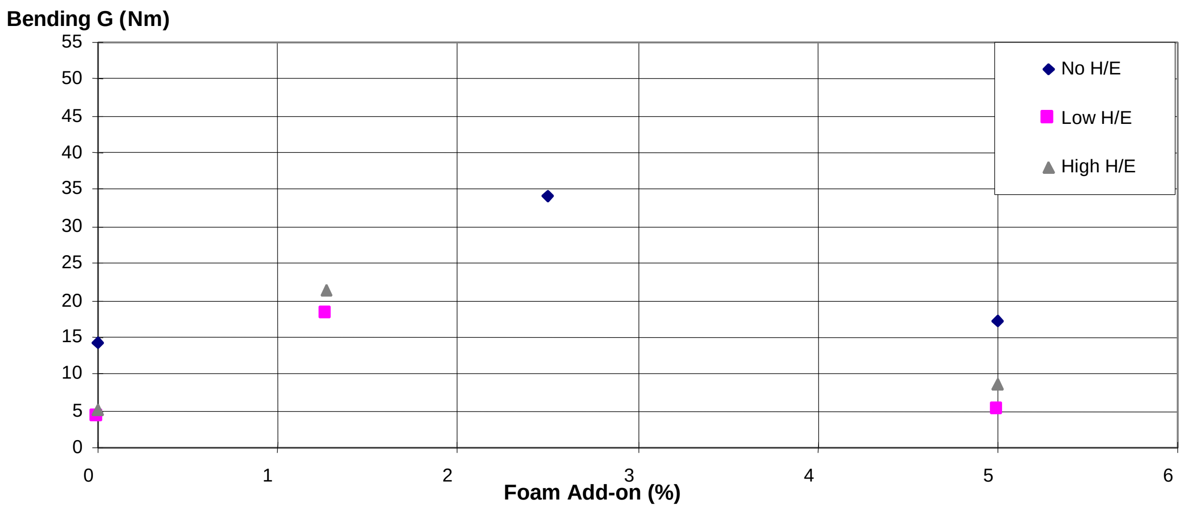

Figure 18: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) bending rigidity, for a 30% wood pulp / 70% polyester blend.

For a 60% wood pulp fabric:

HYDROENTANGLEMENT

Figure 19 clearly shows that the non-hydroentangled webs are the stiffest and the statistics concur (p-value = 0.0001). There is no difference in the two levels of hydroentanglement (p-value = 0.82 >>0.05). The hydrogen bonding effect appears to be responsible for the stiffness of the non-hydroentangled webs; Note the increased stiffness of the webs with 60% wood pulp, Figure 19, as compared to that with the 30% wood pulp, Figure 18. Hydroentangling the webs breaks these hydrogen bonds and physically rearranges the fibers. The consequence is more flexibility, because of the open spaces between fibers caused by water jet holes.

FOAM BONDING

There are no bending rigidity penalties for adding foam provided the web is hydroentangled (p-value = 0.329 >>> 0.05). We fail to show evidence of a difference between the four levels of foam add-on, at 5% significance level. In regards to foam bonding effect, the low binder add-on does not affect the softness of 60% wood pulp / 40% polyester fabric. This is probably the most important result of this research. The positive effect of the binder add-on, on strength and elongation of the fabric, remains a plus.

The corresponding data and their statistical analysis are given in Appendix 7.

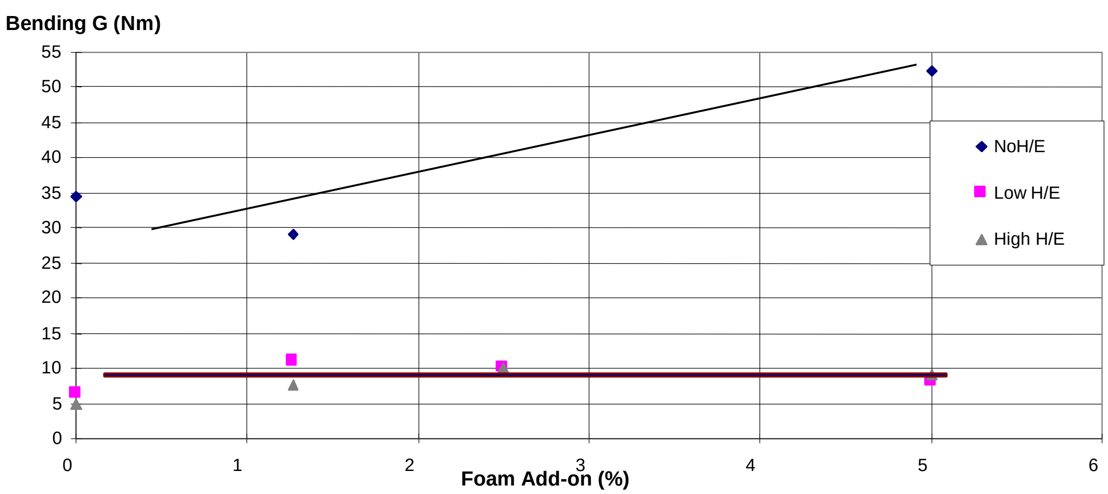

Figure 19: Effect of foam bonding at three levels of hydroentanglement on average (CD and MD) bending rigidity, for a 60% wood pulp / 40% polyester blend.

6.2.5 Subjective softness test

There is no single reliable method to measure softness quantitatively. There are several estimates. Bending rigidity is one such estimate. The most trustworthy method is to run subjective panel surveys, although it is expensive, time consuming, complicated and still may be not perfect. A very informal subjective test was carried out as follows: ten people were asked to compare two fabrics: one with 30% wood pulp and one with 60% wood pulp. Both fabrics were treated alike: low level of hydroentanglement and 5% foam add-on. They used ranking of one for soft and two for stiff. They all agreed that the 30% wood pulp blend fabric was softer, which correlated with the bending rigidity test.

Next, they were asked to rank four fabrics according to their sense of touch. The ranking scale of one (softest) ranking to four (stiffest) was used. In this case, there was a difference between what people felt and what the cantilever test indicated, see Table 8:

Table 8: Comparison of two softness assessments

Fabrics	A	B	C	D
Bending: rank (Nm)	1 (6.4)	2 (8)	3 (34.4)	4 (52.2)
Softness: rank (Subjective)	2 (1.9/4)	3 (2.6/4)	1 (1.7/4)	4 (3.6/4)

We found that even if this test was very informal and tremendously lacking of replicates, people's feelings and standard tests do not agree. The fabric C was very stiff according to the standard test, with a value of 34.4, and people felt it was the softest. Not feeling the difference between fabric A (6.4 Nm) and fabric B (8 Nm) is acceptable and understandable, but ranking fabric C (34.4 Nm) first is definitely a strong disagreement with the standard test. However, in textiles, softness is a very important criteria, and no matter what the standard tests give, it is what people feel and think that would make the difference between buying or not buying.

6.2.6 Relation between softness and load at 5% strain

The literature [23] relates the load at 5% strain as a linear function of the bending rigidity or the Young's Modulus as a linear function of the bending rigidity. No correlation was found when the statistical analysis included both blend levels. Since the two blends behaved differently in terms of softness, we refined our model by analyzing them separately.

We found:

- **For a 30% wood pulp fabric**, neither the load at 5% strain, nor the Young's modulus could be correlated with the bending rigidity.

  For the load at 5%: p-value = 0.59 >> 0.05 and R^2 = 0.025.

  For the Young's modulus: p-value = 0.070>> 0.05 and R^2 = 0.247.

- **For a 60% wood pulp fabric**, both the load at 5% strain, and the Young's modulus had a good correlation with the bending rigidity. However, correlating the bending rigidity with the Young's modulus was the most accurate, with R^2 = 0.79, and p-value = 0.0001, regardless of the direction. See Figures 20.

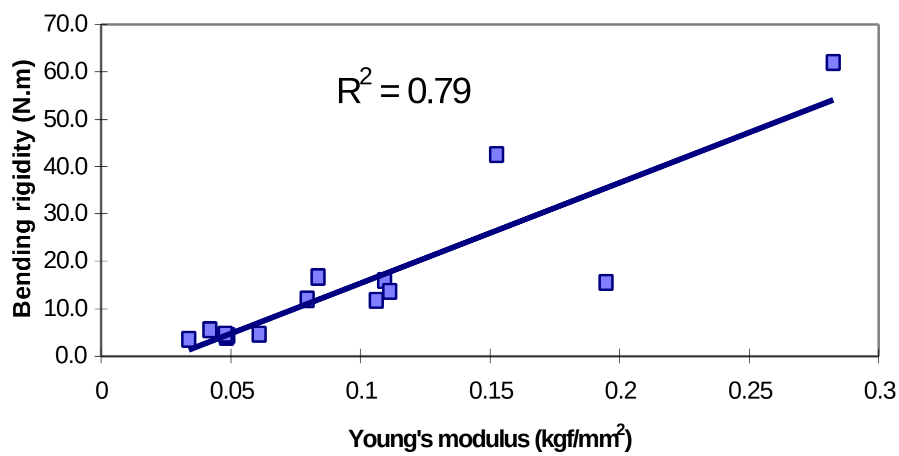

Figure 20: Young's modulus vs. Bending rigidity correlation, for a 60% wood pulp/ 40% Polyester blend, in any direction.

6.2.7 Abrasion

Abrasion resistance proved to be very sensitive to which side was tested. Table 9 shows the abrasion resistance for the fabric side with foam, while figures 21 and 22 refer to fabrics tested on the side free of foam. The side with foam showed no resistance to abrasion; with less than 6 to 8 rotations the fabric was torn apart, regardless of the blend. Although, we note that increasing the binder add-on and the hydroentanglement energy, both increase the resistance to abrasion. However, the effect is very small.

Table 9: Abrasion cycles before breakage, on the side with foam

30 % wood pulp

	0 %	1.25 %	2.5 %	5 %
No H/E	1	n/a	3	3
Low H/E	1.5	7.5	n/a	6
High H/E	1.5	6	5.5	8

60 % wood pulp

0 %	1.25 %	2.5 %	5 %
1	1	n/a	3
2	2.5	3.5	3
2	3	3.5	6

The side without foam turned out to be much more resistant to abrasion.

For a 30% wood pulp fabric, see Figure 21:

HYDROENTANGLEMENT

There is a significant hydroentanglement effect on abrasion (p-value = 0.01). Furthermore, there is a significant difference between hydroentangling and not (p-value = 0.0243). There is no difference between the two levels of specific energy (p-value = 0.352), at a 5% significance level.

FOAM BONDING

Increasing the binder add-on increases the resistance to abrasion (p-value = 0.002) proportionally.

The best statistical model, for a 30% wood pulp fabric, is a linear one with a $R^2 = 0.82$:

Abrasion (# rotation) = -6.81 + 29.83 Specific energy (hp-hr/lb.) + 5.11 Foam (% add on) (8)

Data and analysis are given in Appendix 8.

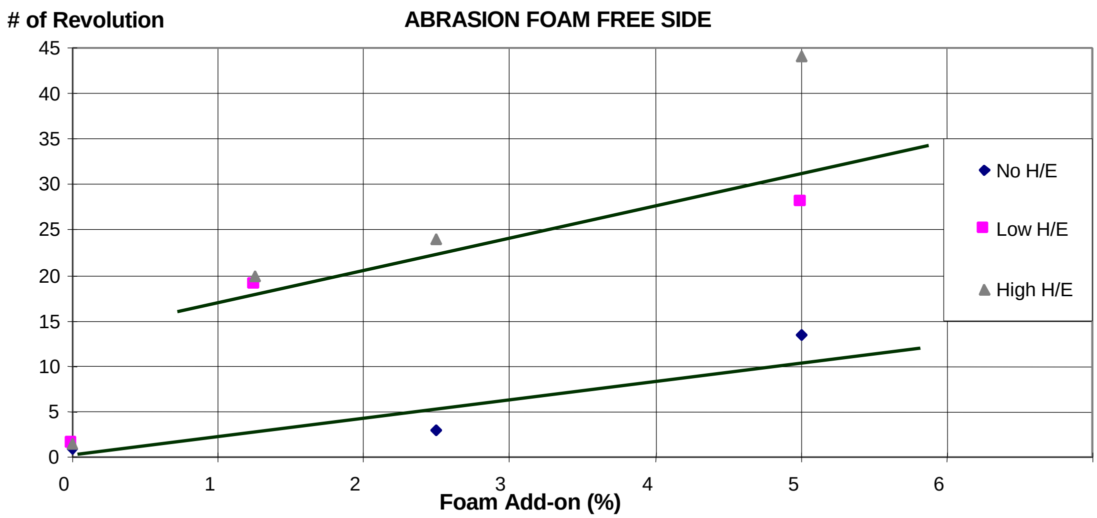

Figure 21: Effect of foam bonding at three levels of hydroentanglement on abrasion resistance for a 30% wood pulp 70% polyester blend.

For a 60% wood pulp fabric, see Figure 22:

At 5% significance level hydroentanglement was not a significant parameter (p-value = 0.99). However, there is a strong binder add-on effect (p-value = 0.0004).

The best statistical model is a straight line with $R^2 = 0.81$.

$$\textbf{Abrasion (\# rotation) = 1.526 + 3.546 Foam (\% add on)} \qquad (9)$$

Data and analysis are given in Appendix 8.

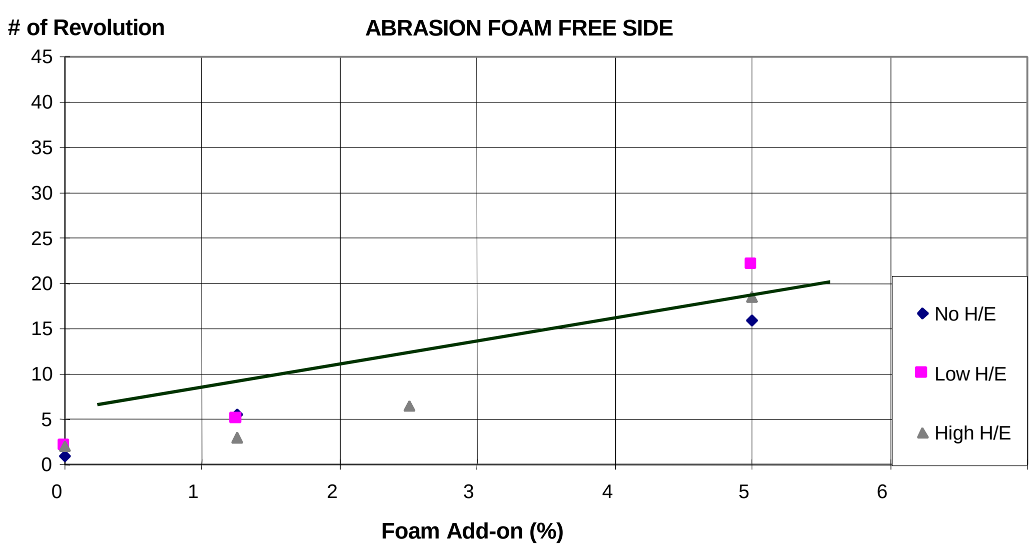

Figure 22: Effect of foam bonding at three levels of hydroentanglement on abrasion resistance for a 60% wood pulp 40% polyester blend.

7 BALANCE AND TRADE OFF

There is no bending rigidity penalty for adding Rhoplex NW 1845 K for a 60% wood pulp hydroentangled fabric. Furthermore, adding the binder increases strength and abrasion. So, fabrics with 5% foam at low and high levels of specific energy show outstanding properties by combining strength and softness. Since it is cheaper and less time consuming to spunlace at a low level of specific energy, we choose to compare fabrics with one or two of the following treatments: 5% add-on or/and low H/E.

Table 10 compares four different fabrics:

Table 10: Comparison of four treatments

PROPERTIES	No H/E No Foam	Low H/E No foam	No H/E 5 % Foam	Both Low H/E and 5%
Max. Load at Breakage (cN/cm)	67	59	190	145
Elongation at Breakage (%)	2.4	9.7	4.7	15
Abrasion resistance (# Rot.)	1	2	16	22
Bending Rigidity (Nm)	34.4	6.4	52.2	8
Softness (Subjective)	1 (1.7)	2 (1.9)	4 (3.6)	3 (2.6)

We found that the fabric combining both bonding technologies clearly shows the best elongation, the best abrasion resistance, a very close second best bending rigidity value, and the second-best strength resistance.

Another very acceptable fabric is the 60% wood pulp, low level of hydroentanglement, and 2.5 % binder add-on. We found: Strength at breakage: 127 cN/cm,

Elongation at breakage: 11%

Abrasion resistance: 19 rotations

Bending rigidity: 10 Nm

Overall, the fabric shows lesser qualities, but is still acceptable and requires less binder add-on.

Next, we compared the two blends, for fabrics treated at low levels of hydroentanglement and 5% foam add-on.

Table 11: Comparison of two blends

PROPERTIES	Blend: **30% Wood pulp** • H/E: Low • Foam: 5%	Blend: **60 % Wood pulp** • H/E: Low • Foam: 5%
Max. Load at Breakage (cN/cm)	121	145
Elongation at Breakage (%)	14.5	15
Abrasion resistance (# Rot.)	28	22
Bending Rigidity (Nm)	5.2	8
Softness (Subjective)	Softer (100 % agree)	Stiffer

The 60% wood pulp fabric shows 20% more strength than the 30% wood pulp fabric does. The fabric is slightly less resistant to abrasion but both have an equivalent strain resistance. In regards to softness, they have almost the same bending rigidity, but subjectively the 60% wood pulp feels much stiffer.

8 SUMMARY AND CONCLUSION

Some properties were found to depend on whether or not the fabric was hydroentangled and less so on the specific energy level. These properties are therefore Boolean with respect to hydroentanglement.

We found that for a 30% wood pulp - 70% Polyester blend:

Table 12: Summary for 30% wood pulp

Physical properties	Hydroentanglement	Foam bonding
Maximum load	No effect	Linear increase
Elongation at maximum load	Boolean increase	Linear increase
Load at 5 % strain	No effect	Linear increase
Bending rigidity	No effect	No effect
Abrasion	Boolean increase	Linear increase

We found that for a 60 % wood pulp - 40% Polyester blend:

Table 13: Summary for 60 % wood pulp

Physical properties	Hydroentanglement	Foam bonding
Maximum load	No effect	Linear increase
Elongation at maximum load	Boolean increase	Linear increase
Load at 5 % strain	No effect	Linear increase
Bending rigidity	Boolean increase	**No effect for hydroentangled webs**
Abrasion	No effect	Linear increase

CONCLUSIONS

We found that:

1. The carrier screen mesh size, during hydroentanglement, was a critical factor for making the desired fabrics.

2. The fiber loss during hydroentanglement increases linearly with increasing specific energy, in the range studied.

3. The fabric basis weight has a very weak influence on the fiber loss during hydroentanglement.
4. Fabrics hydroentangled from one side only or on both sides lose the same amount of fibers.
5. The physical properties -strength, load at 5% strain, abrasion resistance- are greatly improved with an add-on of binder, while different levels of hydroentanglement energy input were found to be less significant.
6. The hydroentangled and foam bonded fabrics are softer than those which were foam bonded only.
7. The addition of foam bonding up to 5% did not affect the softness of the hydroentangled fabrics.
8. The hydrogen bonding effect is shown to be significant at these levels of hydroentanglement and binder add-on.
9. The fabric bending rigidity can be correlated with the Young's modulus of the bonded fabric for a 60% wood pulp fabric.
10. The abrasion resistance behavior is very different depending on the side tested: foam free or foamed.

Finally, we can clearly answer the following two questions:

1- Is it useful technically to hydroentangle and then foam bond a web?

Yes, combining the two bonding technologies is useful because all physical properties are enhanced while the softness is maintained.

2- Is it worth doubling the wood pulp content?

Yes, due to better strength and almost equivalent properties. However, if the fabric is to be worn directly on the skin, as in surgical gowns, doubling the wood pulp content wouldn’t be recommended, because of the subjective feelings given by people interviewed. Possible applications of the 60% wood pulp fabric could be: wipes, surgical cover boots, surgical hats or interlining.

9 RECOMMENDATIONS

The combination of the two bonding technologies was done at a very light basis weight. Lighter fabrics could hardly be produced from the wet lay machine and hydroentangled properly under the process conditions studied. All trends in physical properties would probably be enhanced with heavier fabric basis weight. Therefore, there is no need to look for heavier fabric basis weight.

In regards to blend levels, we were able to notice the hydrogen bonding effect, so there is no need to further investigate in this area.

Machine set up for hydroentanglement and foam bonding were chosen in such a way that they really represent what industry calls “low level” of bonding.

I think we have extensively covered the subject, and there is no real interest in looking for other experimental conditions. However, a closer understanding of the bonding mechanisms at the macro and micro levels of hydroentanglement could be very interesting, especially understanding the relation between water jets, fibers and wire screen. A lot of work needs to be done in the wet lay dispersion tank because it runs poorly in terms of reliability.

LIST OF REFERENCES

(1) S. K. Batra. Fiberweb and nonwoven production. *TT305Class Notes NCSU*, Fall 97.

(2) *The Nonwovens Handbook*, INDA, Cary (NC),1988.

(3) Du Pont Company. Sontara spunlaced fabric finishing. *Journal of Research Disclosure*, 138, October 1975.

(4) C. M. Daily. Latest advances in the hydroentanglement technology. *Nonwoven Fabrics Forum*, at Clemson University, June 1989.

(5) T. M. Gilmore, N. B. Timble, and G. P. Morton. Hydroentangled unbleached cotton, *Proceedings, TAPPI Nonwovens conference*, Atlanta (GA),1996.

(6) Guerin. *U.S. Pat. No. 3,214,819*, November1965.

(7) B. Kirayoglu and D. Zafiroglu. Woodpulp-polyester spunlaced fabrics. *U.S. Patent 4,442,161*, issued to E.I. Du Pont de Nemours and Company, April 1984.

(8) P. Ziehl. The aquajet spunlace system - A new development for spunlace products. *Proceedings, TAPPI Nonwovens Conference*, Memphis (TN), 273-289, March 1997.

(9) P. Coppin. Spunlace bonding- world activity. *Nonwovens World*, :89-95, May 1997.

(10) C. M. Daily. Aspects of hydraulic entanglement technology, *TAPPI Journal*, 71(10):152-154, 1988.

(11) W. S. Barnard and R.J. Osborne. Spunlace processes worldwide. *INDA-TEC 86 Conference* 1986.

(12) P. Specklin. New Developments in Hydraulic Consolidation. *Industrie Textile*, (1279):47-50, September 1996.

(13) J. M. Oelkers and E. J. Sweeney. Latex binders and binding techniques for disposable nonwovens. *TAPPI Journal*, 71(8):69-76, 1988.

(14) H. C. Morris and M. Mlynar. Chemical binders and adhesives for nonwoven fabrics. *INDA-TEC 95 Books of Paper*, Cary (NC), 123-136, 1995.

(15) Personal communication with M. Mlynar, of Rohm and Haas Company, based on an article from P. M. Westfall, W. Conn, and R. L. Brown. Foam latex systems technology and application.

(16) G. C. Kantner. Froth Backcoating of Upholstery fabrics. *America's Textiles*, February 1983.

(17) W. E. Devry. The Chemistry and Formulation of Latex Nonwoven Binders. *Nonwoven Fabric Forum*, at Clemson University, June 1989.

(18) R. Bell. Acrylic Polymers. *TAPPI Notes– Nonwovens Binders and Additives Seminar*, Atlanta (GA), 19-23, 1988.

(19) R. Pangrazi. Chemical Binders for Nonwovens - A Primer. *INDA Journal of Nonwovens Research*, 4(2): 33-36, 1992.

(20) K. Denbigh. *The principles of chemical equilibrium with applications in chemistry and chemical engineering*, 83-84, 1961.

(21) *Gaston County Foam Unit Instructions Book.* Gaston County Dyeing Machine Company, Charlotte (NC).

(22) Personal communications with Mr. Hermann Neupert of Gaston County Dyeing Machine Company, Consultant, June 1998.

(23) A. Shahani. Foam latex bonding of spunlace to improve its physical properties. *Master Thesis*, North Carolina State University, 1997.

(24) B. A. Brooks, J. W. Kennette, and C. Buyofsky. Lightly entangled and dry printed nonwoven fabrics and methods for producing the same. *U.S. Patent 4,623,575*, issued to Chicopee, November 1986.

(25) H. Viazmensky, C. E. Richard, and J. E. Williamson. Water entanglement process and product. *U.S. Patent 5,009,747*, issued to The Dexter Corporation, June 1989.

(26) A. W. Meierhoefer. Wet-laid nonwovens- A survey of the fundamentals of making specialty fabrics on papermaking machinery. *Nonwoven Fabric Forum*, at Clemson University, June 1989.

(27) Personal communication Bruderhauser, *Neue Bruderhaus Data Sheet* .

(28) ASTM D-1117-97: Standard test methods for nonwoven fabrics.

(29) ASTM D-5732-95: Stiffness of nonwoven fabrics using cantilever test.

(30) ASTM D-5035-95: Breaking force and elongation of textile fabrics (strip method).

(31) ASTM D-3884-92: Abrasion resistance of textile fabrics (Taber Rotary platform).

APPENDICES

Appendix 1: Calculation of Specific Energy (SE)

SE is the Specific Energy given to the web [5].

$$\textbf{Specific Energy} = (K\ J\ d^2\ C_d\ P^{3/2}) / \sqrt{r}\ S\ W$$

$K = 60 * 1000^{1.5}\ \Pi / \sqrt{8}$
J: number of jets per meter
d: diameter of the jets, (m)
C_d: coefficient of discharge
P: pressure of the jets, (N/m^2)
r : density of water, (g/m^3)
S: conveyor speed, (m/min)_
W: fabric basis weight, (g/m^2)

Low level of Hydroentanglement

Parameters			
J (1/m)	1575	1575	1575
d (m)	1.27E-04	1.27E-04	1.27E-04
Cd	0.7	0.7	0.7
pressure(PSI)	200	400	600
pressure (N/m^2)	1379310.345	2758620.69	4137931.035
density (g/m^3)	1000000	1000000	1000000
speed (m/min)	4.572	4.572	4.572
weight (g/m^2)	50	50	50
K	2107444.419	2107444.419	2107444.419
SE (KJ/kg)	2.656E+02	7.511E+02	1.380E+03
Total	2,397	0.405	

High level of hydroentanglement

Parameters			
J (1/m)	1575	1575	1575
d (m)	1.27E-04	1.27E-04	1.27E-04
Cd	0.7	0.7	0.7
pressure(PSI)	200	400	600
pressure (N/m^2)	1379310.345	2758620.69	4137931.035
density (g/m^3)	1000000	1000000	1000000
speed (m/min)	6.096	6.096	6.096
weight (g/m^2)	50	50	50
K	2107444.419	2107444.419	2107444.419
SE (KJ/kg)	1.992E+02	5.633E+02	1.035E+03
Two passes	**x 2**		
Total	3,595	0.608	

Appendix 2: Fiber loss data

```
Linear model: loss as a function of fabric weight and SE.

                          Analysis of Variance

                          Sum of         Mean
 Source          DF      Squares       Square       F Value       Prob>F

 Model            2     21.45669     10.72834        21.406       0.0006
 Error            8      4.00940      0.50117
 C Total         10     25.46609

     Root MSE       0.70794     R-square       0.8426
     Dep Mean       4.05136     Adj R-sq       0.8032
     C.V.          17.47404

                          Parameter Estimates

                   Parameter      Standard    T for H0:
  Variable  DF      Estimate         Error   Parameter=0    Prob > |T|

  INTERCEP   1      2.739737    0.93679647         2.925        0.0192
  W          1     -0.009322    0.00647891        -1.439        0.1882
  SE         1      4.104013    0.74963705         5.475        0.0006
```

Basis Weight	SE	Loss
g/m^2	Hp-hr/lb	%
59.4	0.584	5.09
59.4	0.584	4.33
59.4	0.811	6.33
96.1	0.361	1.82
96.1	0.361	3.296
96.1	0.501	3.9
96.1	1.286	6.815
147	0.236	2.367
147	0.236	2.496
147	0.328	3.49
147	0.841	4.631

Appendix 3: T test : Comparison of H/E sides for two passes

We compared at low level of hydroentanglement, fabrics entangled on one side twice, and fabric entangled on each side once.

Ho: There is no difference between the two treatments.
H1: There is a difference between the two treatments.

	59.4 g/m^2	96.1 g/m^2	147 g/m^2
Same side twice	4.33	3.296	2.496
Each side once	5.09	1.82	2.367
Difference	- 0.76	1.476	0.129

Mean of the paired differences: 0.845

Standard deviation: 1.1257

T-test: t= mean of the paired differences * $\sqrt{n}$ / st. dev.

T= 0.845* $\sqrt{3}$ /1.1257 = 1.3

$T_{0.025,2}$ = 4.303 abs(t_{cal})=1.3 < 4.303 so we cannot reject Ho.

Appendix 4: Maximum load analysis: (CD+MD)/2

All data, model: foam and H/E

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	0.20388	0.10194	17.816	0.0001
Error	18	0.10299	0.00572		
C Total	20	0.30687			

Root MSE	0.07564	R-square	0.6644
Dep Mean	0.27868	Adj R-sq	0.6271
C.V.	27.14333		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	0.139825	0.03508666	3.985	0.0009
F	1	0.049337	0.00840948	5.867	0.0001
H	1	0.082560	0.06666632	1.238	0.2315

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
compare low-high	1	0.0090403	0.0090403	1.56	0.2289
compare no and low-high	1	0.0036531	0.0036531	0.63	0.4384

OBS	BLEND	H/E	F	CD	MD	Average Load (kgf)
1	30	0.00	0.00	0.03741	0.03784	0.03763
2	30	0.00	2.50	0.24984	0.35546	0.30265
3	30	0.00	5.00	0.55200	0.36454	0.45827
4	30	0.40	0.00	0.10770	0.14710	0.12740
5	30	0.40	1.25	0.29379	0.38364	0.33872
6	30	0.40	5.00	0.25102	0.33722	0.29412
7	30	0.61	0.00	0.05519	0.08859	0.07189
8	30	0.61	1.25	0.25805	0.52644	0.39225
9	30	0.61	2.50	0.22079	0.45554	0.33817
10	30	0.61	5.00	0.34095	0.46712	0.40404
11	60	0.00	0.00	0.13746	0.20886	0.17316
12	60	0.00	1.25	0.20430	0.26307	0.23369
13	60	0.00	5.00	0.36074	0.36074	0.36074
14	60	0.40	0.00	0.09358	0.21154	0.15256
15	60	0.40	1.25	0.14861	0.23490	0.19176
16	60	0.40	2.50	0.22214	0.43590	0.32902
17	60	0.40	5.00	0.24145	0.50792	0.37469
18	60	0.61	0.00	0.10134	0.24136	0.17135
19	60	0.61	1.25	0.16342	0.31488	0.23915
20	60	0.61	2.50	0.24950	0.60670	0.42810
21	60	0.61	5.00	0.32460	0.54120	0.43290

To change the Max load (N)at breakage to the linear stress Max Load in (cN/cm), just divide by 2.54 (width of the samples tested) and multiply by 100.

It doesn't change the statistical analysis, but the values of the estimate of the parameters.

Appendix 5: Strain analysis: (CD+MD)/2

All data, model: foam and H/E

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	440.40969	220.20485	61.347	0.0001
Error	18	64.61130	3.58952		
C Total	20	505.02099			

Root MSE	1.89460	R-square	0.8721
Dep Mean	10.43769	Adj R-sq	0.8578
C.V.	18.15154		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	2.116773	0.87881126	2.409	0.0269
F	1	0.937670	0.21063107	4.452	0.0003
H	1	17.105740	1.66978306	10.244	0.0001

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
Low-high H/E	1	3.39874	3.39874	1.66	0.2150
No H/E vs. low-high H/E	1	399.91577	399.91577	195.23	0.0001

OBS	BLEND	H/E	F	CD	MD	Average Strain (%)
1	30	0.00	0.00	3.3514	2.6089	2.9802
2	30	0.00	2.50	2.9429	2.4410	2.6919
3	30	0.00	5.00	7.8199	5.6562	6.7380
4	30	0.40	0.00	16.2188	10.5591	13.3889
5	30	0.40	1.25	9.7950	11.0552	10.4251
6	30	0.40	5.00	21.4207	7.5296	14.4751
7	30	0.61	0.00	12.0423	8.1312	10.0868
8	30	0.61	1.25	14.5014	8.3439	11.4226
9	30	0.61	2.50	16.3189	10.2940	13.3065
10	30	0.61	5.00	24.0929	10.8038	17.4484
11	60	0.00	0.00	2.5801	2.1300	2.3550
12	60	0.00	1.25	2.3170	1.8504	2.0837
13	60	0.00	5.00	4.8950	4.5171	4.7061
14	60	0.40	0.00	11.2767	8.1391	9.7079
15	60	0.40	1.25	13.3071	8.4744	10.8908
16	60	0.40	2.50	12.4656	15.7796	14.1226
17	60	0.40	5.00	12.2851	18.7140	15.4996
18	60	0.61	0.00	15.1624	8.6955	11.9290
19	60	0.61	1.25	15.6234	12.1418	13.8826
20	60	0.61	2.50	15.0050	9.9685	12.4867
21	60	0.61	5.00	18.7451	18.3833	18.5642

Appendix 6: Average load at 5 %: (CD+MD)/2

Model: Blend, H/E and Foam

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	24610.21460	8203.40487	7.300	0.0030
Error	15	16856.29222	1123.75281		
C Total	18	41466.50683			

Root MSE	33.52242	R-square	0.5935
Dep Mean	104.12014	Adj R-sq	0.5122
C.V.	32.19590		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	30.122786	34.57426924	0.871	0.3973
BLEND	1	0.688872	0.53197080	1.295	0.2149
F	1	17.737846	3.89934392	4.549	0.0004
H	1	1.293470	34.58823788	0.037	0.9707

Model: H/E and Foam

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	22725.81587	11362.90793	9.701	0.0017
Error	16	18740.69096	1171.29319		
C Total	18	41466.50683			

Root MSE	34.22416	R-square	0.5481
Dep Mean	104.12014	Adj R-sq	0.4916
C.V.	32.86987		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	67.667175	19.22996928	3.519	0.0028
F	1	17.187424	3.95724784	4.343	0.0005
H	1	-7.727000	34.58873878	-0.223	0.8261

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
compare low-high	1	1336.3703	1336.3703	1.19	0.2926
compare no and low-high	1	674.1581	674.1581	0.60	0.4505

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
compare 0% vs. rest	1	24214.556	24214.556	28.32	0.0001

60% wood pulp only, low H/E and high H/E only

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	14392.62178	7196.31089	12.571	0.0112
Error	5	2862.24455	572.44891		
C Total	7	17254.86632			

Root MSE	23.92590	R-square	0.8341
Dep Mean	108.27067	Adj R-sq	0.7678
C.V.	22.09823		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	4.769033	42.74267535	0.112	0.9155
F	1	22.087068	4.57550810	4.827	0.0048
H	1	109.279560	80.56271127	1.356	0.2330

60% wood pulp only, all data: no H/E, low H/E and high H/E

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	2	21583.45801	10791.72900	20.467	0.0007
Error	8	4218.26627	527.28328		
C Total	10	25801.72427			

Root MSE	22.96265	R-square	0.8365
Dep Mean	110.22781	Adj R-sq	0.7956
C.V.	20.83199		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	61.143276	14.65605759	4.172	0.0031
F	1	22.972713	3.59104282	6.397	0.0002
H	1	-1.403975	28.60745498	-0.049	0.9621