Hydroentanglement technology applied to wet-formed and other precursor webs

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ABSTRACT *Hydroentanglement or spunlace technology has become a major "bonding" technology for nonwovens because it yields products with unique characteristics that are difficult to achieve by other bonding techniques. Most spunlaced products have been produced from a dry-laid precursor web, either carded or air-formed. Dexter Nonwovens has produced spunlaced nonwovens from wet-formed precursor webs, which will have effects on future product developments. Here, we examine some of the developments, problems, and potential solutions in applying spunlace technology to wet-formed precursor webs, either alone or in combination with other web processes.*

KEYWORDS
Bonding
Cellulose
Fibers
Nonwovens
Physical properties
Wet forming

"Hydroentanglement," "water jet entanglement," and "spunlacing" are all terms used to describe a process for imparting strength or structural integrity to an array of fibers or a nonwoven web. It is not a nonwoven process by itself but is only one step in the process of creating a sheet structure from loose fibers.

The entanglement process consists of subjecting fibers in a web to fine, high-pressure jets of water. These jets are usually arranged in multiple rows and are directed at the fibrous web that is supported and carried by a moving screen. As these fibers pass under the high-pressure water jets, they tangle and form a sheet structure.

Hydroentanglement is an energy transfer process that changes and strengthens the array of loose fibers, imparting the desired physical, tactile, and aesthetic properties. There are many ramifications, variables, and parameters in the hydroentanglement process.

Patents

From 1963 into the 1970s, DuPont established five patents that were to become the core of the hydroentanglement process. Through the May 23, 1976 Federal Register, DuPont released these key patents into public domain. The patents were:

1. U.S. 3,485,706, Evans, 1969
2. U.S. 3,486,168, Evans, 1969
3. U.S. 3,493,462, Bunting, 1970
4. U.S. 3,494,821, Evans, 1970
5. U.S. 3,508,308, Bunting, 1970.

Releasing these patents led to further developments in the hydroentanglement field, especially in Japan. One notable group was Asahi Chemical Industry. It used fluid jets to entangle very fine fibers produced from splittable composite fibers to produce substrates used to form synthetic suede leather products.

M. Suzuki of Uni-Charm Corp. used reflected energy from the water jet stream to intensify web entanglement. This was achieved by using impervious backing systems based on rolls, curved plates, etc. (Uni-Charm has recently begun using water-pervious backing materials in combination with deflectors for more effective entanglement.)

Uni-Charm's industry developments led Dexter Nonwovens to apply this technology to wet-formed precursor webs. Sophisticated turnkey hydroentanglement systems have been developed by other independent machinery suppliers such as Honeycomb Systems (United States and France, now owned by Valmet Machinery of Finland) and Perfojet (France).

The process

Hydroentanglement is a process that imparts tensile strength and other properties to a web structure. Other process steps can take place in a typical nonwoven process in addition to those unique to hydroentanglement. These steps can affect the system performance and the character and properties of the products. Major steps in a hydroentanglement system are:

- The web-forming process, in which the chosen fibers are formed into a precursor web, often unbonded, for hydroentanglement
- The web support system, which transports the precursor web through the entanglement system
- The entanglement system
- The water circulation system to supply the hydroentanglement jets
- The web drying process.

More comprehensive information about the process technolgy is available in other publications (*1-3*).

I. Characteristics of pulp fibers

Pulp source	*Length, mm*	*Diameter, mm*	*Ratio*
Woods			
Coniferous	4.0	40	100
Deciduous	2.0	22	90
Straws and grasses			
Rice	0.5	9	60
Esparto	1.1	10	110
Canes and reeds			
Bagasse (sugar cane)	1.7	20	80
Miscellaneous	1.2	12	100
Bast fibers*			
Linen	55	20	2600
Ramie	130	40	3500
Leaf fibers			
Abaca (Manilla hemp)	6	24	250
Sisal	2.8	21	130
Seed fibers			
Cotton	30	20	1500
Cotton linters	20	20	1000

*Fibers obtained from inner bark.

Precursor web formation

Both DuPont and Chicopee have developed and patented unique precursor web-forming systems (*4, 5*) based on card or air forming techniques to produce high throughput rates and webs of high quality.

Carding technology applies a combing technique to a loose assembly of fibers in a textile process which produces an aligned batt of fibers as a precursor web. By further treatment, known as cross lapping, it is possible to build up a composite batt which has less directionality but is still highly directional when compared to a wet-formed web. Air-form technology uses patented technology which combs out the fibers and transports them in an air stream to separate and randomly distribute the fibers prior to formation of the precursor web.

In the early development work in hydroentanglement, DuPont and Chicopee made use of fibers and web-forming techniques with which they were familiar. So it remained until 1987, when Uni-Charm licensed the technology to Dexter. The idea of using wet-formed precursor webs is therefore relatively new.

There is great potential in using wet forming to produce precursor webs for hydroentanglement. But there are also some formidable, practical problems to be overcome concerning the critical element—the fibers used.

Fiber selection

Wet forming is a well-established nonwoven web process in paper technology (*6, 7*) and is remarkably versatile in the use of fibers to produce webs. Although the fibers handled by a wet-forming system are shorter than a card system, this shorter length does not necessarily result in a problem for entangled fabrics.

Let's look at the most advantageous fiber that can be used for wet-forming technology—cellulose.

Cellulose fibers

Cellulose determines the fiber character, its success in papermaking, and its efficiency in wet-forming a nonwovens web. The cellulose pulp characteristics shown in **Table I** reveal how fibers of different dimensions can be created from various cellulose sources to become a good source for hydroentanglement.

Behavior of cellulosic fibers with water

Cellulosic fibers exhibit a number of unique, naturally occurring properties. These fibers:

- Have a high tensile strength
- Are supple
- Resist plastic deformation
- Are water insoluble
- Are hydrophilic
- Have a wide range of dimensions
- Have an inherent bonding ability
- Can absorb modifying additives
- Are chemically stable
- Are relatively colorless.

The best balance of these properties occurs when most of the lignin is removed from the fibers and substantial amounts of hemicellulose are retained.

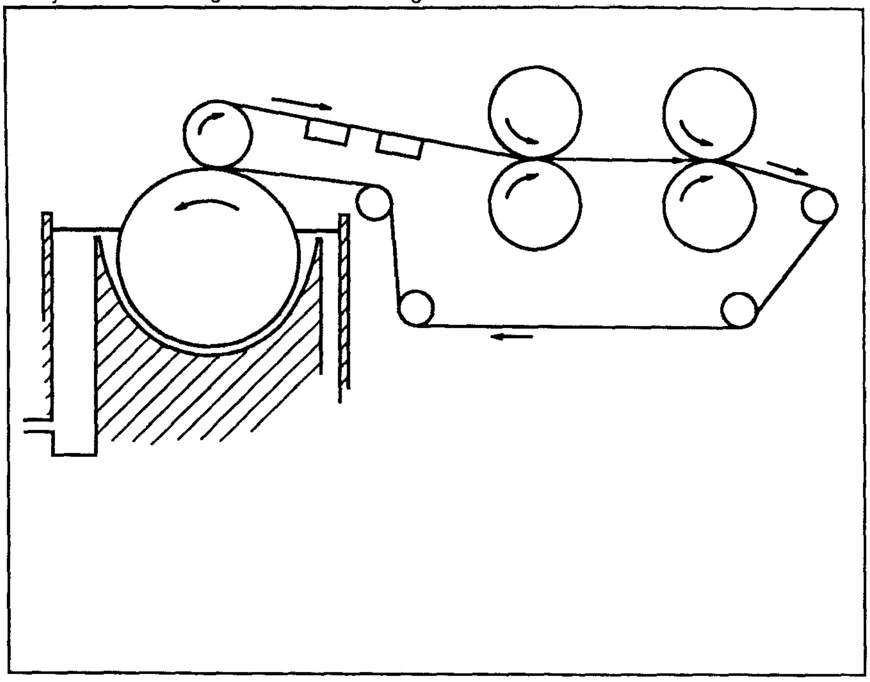
Fiber properties are also enhanced by beating or refining, which removes the primary fiber walls and allows the fibers to hydrate and swell, increasing their flexibility and bonding power.

The hydrophilic nature of cellulosic fibers is also important, since the wet-forming process occurs in an aqueous medium. The fibers readily absorb water and are easily dispersed in a water suspension. When wet fibers combine during the web forming operation, bonding occurs by the polar attraction of the water molecules for each other and for the hydroxyl groups covering the cellulose surface. As the water evaporates, the hydroxyl groups of the cellulose surfaces link together by hydrogen bonds.

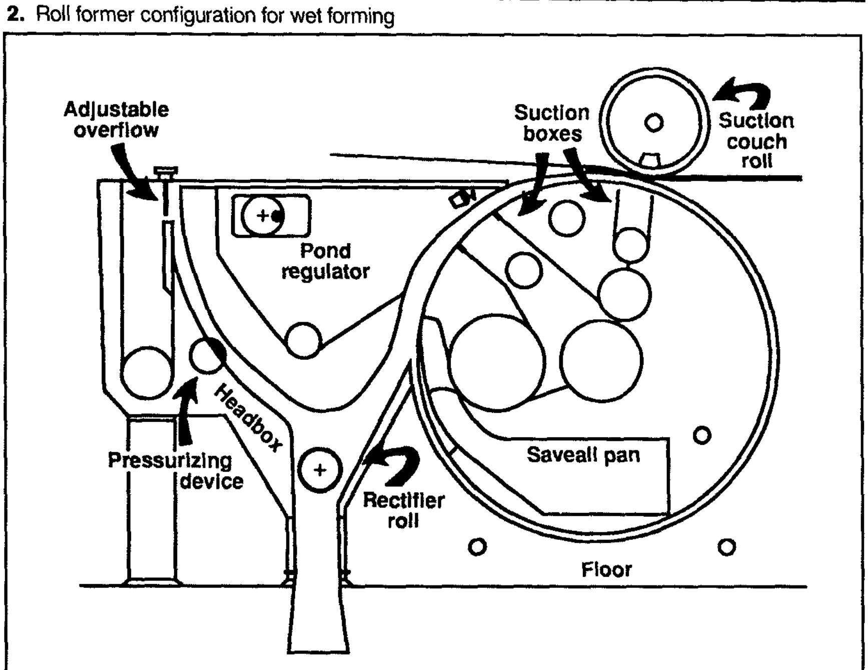
A paper's strength depends not only on the fibers' high tensile strength but also on the bonds between fibers. Beating or refining improves bonding at the expense of individual fiber strength.

To achieve the best possible en-

1. Cylinder mold configuration for wet forming



2. Roll former configuration for wet forming



tangled web, it is important to select a range of cellulose fibers, refine them through techniques borrowed from paper technology, and modify the fiber characteristics while they are wet. The combination of these two aspects of cellulose fiber technology can give us great flexibility in controlling fiber properties at the precursor web stage.

Man-made fibers

There is little advantage in applying hydroentanglement to a pulp fiber web of 100% cellulose, although the rearrangement of wet, well-refined cellulose fibers by such a technique could produce some interesting webs. Most wet-formed precursor webs are produced from mixtures of cellulose fibers and man-made fibers. Although there are constraints in fiber length, it is difficult to wet form fibers above 15-18 mm in length.

The wet forming of mixed fiber webs offers an extremely wide range of products. Cellulosic fibers such as rayons are easily entangled. Polyesters, acrylics, nylons, etc. exhibit varying degrees of ease of entanglement, usually related to fiber stiffness, and these can be easily formed wet. Inorganics such as glass and carbon, of the right length and decitex, can be mixed in varying quantities in wet-formed webs. High-performance fibers such as Kevlar® and P84® can be formed readily by wet-form nonwoven technology.

The wet-formed precursor web does not have to contain cellulose fiber at all, but it could consist of a blend of glass fiber with P84 imide fiber or some other totally synthetic formulation.

Precursor web forming technology

The formation of the precursor web for entanglement is best achieved by using wet-formed nonwoven systems. Machine systems based on the cylinder mold concept can easily form many of the fiber systems, as will the roll formers and inclined wire systems (**Figs. 1-3**).

Wet-forming systems are fast compared with other web forming technologies, they are efficient, and they can form a sheet that can be almost perfectly isotropic, as opposed to one that has a high degree of directionality.

Webs can be produced that are multilayered structures of different layer compositions. Wet-formed precursor webs can be produced in web weights from 10 g/m^2 up to 1000 g/m^2. For effective entanglement, however, web weights below 30 g/m^2 are too light because there are too few fibers per unit mass.

A portion of the fiber should be "long fibered" if the principal component is to be short-fibered wood pulp (*1*). Vuillaume suggests requiring 25-30% of such fibers to produce a structure within the web and ensure good entanglement (*1*).

This does not mean that fibers that are 38 mm in length need to be used (as in carding), because some cellulose fibers are of acceptable length. Work with 6-, 10-, and 15-mm synthetic fibers has resulted in successful entanglement.

Entanglement technology

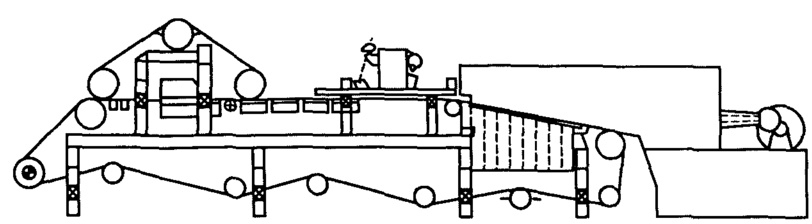
The wet-formed precursor web can be dried, sprayed, surface coated, etc., in the conventional way for wet-formed nonwovens. The ability to treat a wet, never dried, wet-formed nonwoven structure is the advantage of the wet-formed precursor web.

This does not mean the entanglement section must be in line to achieve the best possible efficiency as in the configuration illustrated in **Figs. 4 and 5**. There are many advantages to reeling the wet-formed web wet, with interleaving, and then using an off-line system to treat the web. Experimental webs have been treated with entanglement systems as illustrated in **Figs. 6 and 7**.

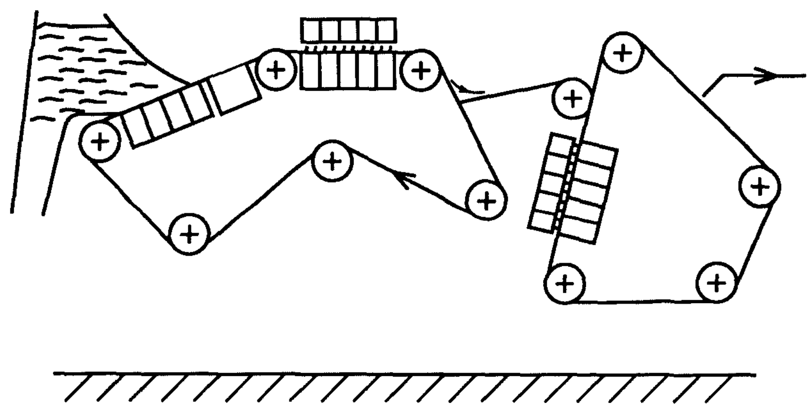
Principal components of any entanglement system are:

1. An entanglement fabric that carries the web to be treated through the process and plays a critical role in the actual entanglement process
2. A system of injectors with a high-pressure water system, using holes 100-120 μm in diameter, arranged in rows with 3-5 mm spacing and 30-80 holes per 25 mm, to create directed and carefully controlled "needles" of water, which cause entanglement.
3. A system of vacuum boxes placed under the entanglement fabric with variable vacuum controls to each box
4. A water recirculation and filtration system
5. A controlled variable-speed drive
6. A system to create energy that pressurizes water up to 2500 psi and then efficiently delivers that energy via the water needles to the web.

3. Inclined wire configuration for wet forming



4. Two-sided entanglement on wet-formed web (8)



Experimental details

Wet-formed precursor webs were produced at nominal 50- and 80-g/m^2 web weight using an inclined wire former, a roll former, or mold system.

Webs were consolidated with a minimum of wet press load to tie surface fibers into the web. Then the webs were reeled wet. To facilitate wet reeling, some webs were interleaved with siliconized paper at the reeler to allow the web to be unwound without damage.

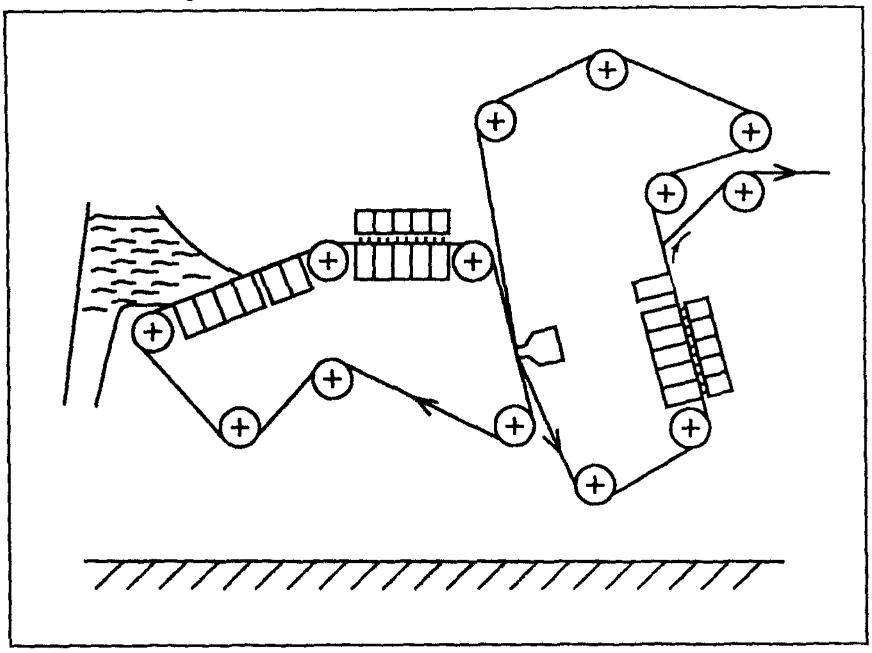
Wet reels for entanglement were sealed in polythene sacks for storage and transportation. Moisture samples were taken at the time of reel up and immediately prior to treatment.

A review of the basic parameters of the hydroentanglement process indicates that the treatment of wet-formed precursor webs should not be fundamentally different from other types of precursor treatment. The differences needing further study are:

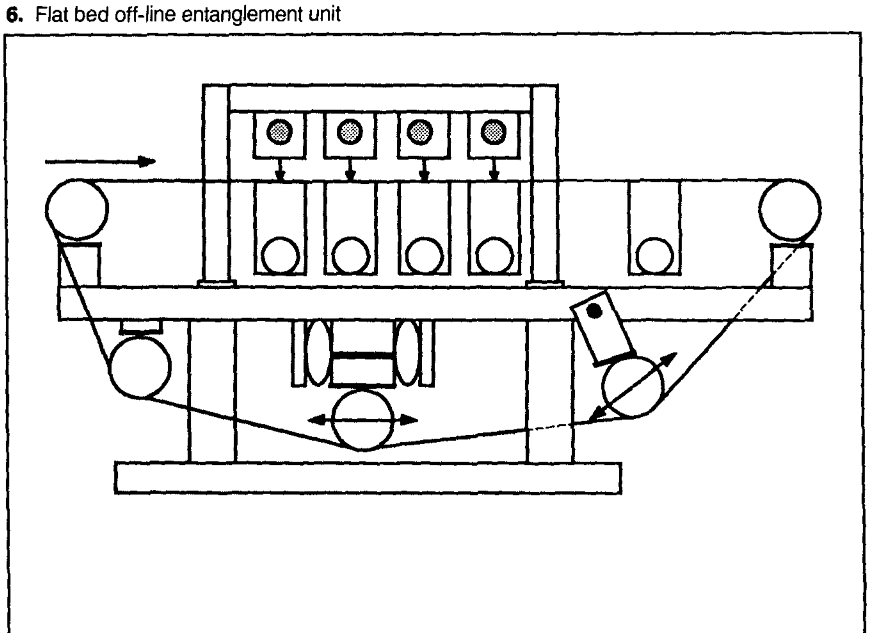
1. The web being treated "never dried" or dried and rewet
2. The fiber damage and fiber loss from the web
3. The effect of speed and/or treatment pressures
4. The effect of different sources of the cellulose fiber fraction.

Previous studies (*1, 2*) using data

5. Two-sided entanglement on wet-formed web (8)



6. Flat bed off-line entanglement unit



obtained from carded or air-laid precursors showed that the web's strength is a result of the water pressure fed to the needles, the energy applied, and the entanglement substrate. This general relationship was the same for wet-formed precursors.

In earlier work, the speed at which the web was treated (up to 90 m/min) seemed to have little effect. While this may be true for some fibers that are entangled easily or for carded web structures, the speed of treatment greatly affects wet-formed precursors.

A fundamental difference with wet-formed webs is whether they were first treated wet or dried. There is an advantage in keeping the web wet, although some workers have reported they found no difference in the webs treated as "never dried" or dried (2). So we designed experiments to study (a) the treatment of "never dried" and dried webs as measured by tensile strength and (b) the effect of different types of cellulose fiber on fiber loss.

All of the experimental webs contained 50% polyester fiber 12 mm long and 1.7 decitex. The other half of the furnish was pulp made up of Southern pine kraft, eucalyptus, secondary cut cotton linter, or manila.

The cellulose fiber fractions were dispersed in water in a small pulper fitted with rotating blades. Pulping was carried out at 2–5% consistency, depending on the fiber, for 20 min or until visual examination showed freedom from fiber bundles. Polyester fiber was added directly to the pulper, and the consistency was reduced to 0.5–1.0% maximum within 10 min of dispersion.

Forming consistencies were adjusted to provide a uniform web but were normally in the 0.03–0.05% range. Reel-up moistures were kept to 45–50% moisture by small adjustments to a felted wet press running virtually off load. Moisture contents of webs, after being stored for up to three weeks and then being transported, did not vary by more than 1%, although free water condensed in the polythene sack.

Entanglement was achieved on an off-line test rig. Webs were run at 10 m/min with 100-μm-diameter water jets arranged in 2 rows per injector and 30 jets/in. in each row. The entanglement fabric was a stainless steel 70-mesh belt. Entanglement pressures were kept the same throughout the experiments **(Table II)**. After entanglement, web samples were air dried for test purposes.

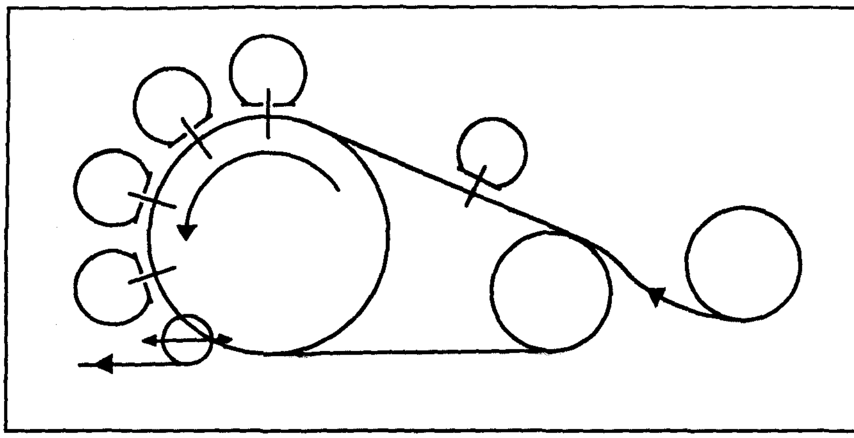
Table III presents the initial test results for the treatment of never-dried webs.

Further experiments were made to examine the effect of drying on the cellulose-containing webs. A potentially important aspect was the "natural" strength of the structure at 50% cellulose derived from the bonding of the cellulose fibers.

Although the wet tensile values on such webs are difficult to measure, the wet web strength without entanglement appears to be high. The effect of entanglement on wet web strength is not well represented by wet tensile value for wet-formed cellulose containing precursor webs.

Similarly, experiments in which the wet-formed webs were first dried and then rewetted prior to entanglement showed no significant differen-

7. Drum type off-line entanglement unit



II. Entanglement pressures used throughout the experiments

Injector	Water pressure, psi Side 1	Side 2
1	300	500
2	500	1000
3	750	1500
4	1000	750

ces in the wet tensile values. However, the webs looked different and showed much wider fluctuations in fiber loss values. This result is caused by the removal of original "fines" material and the breakage of fibers during entanglement. Fibers that have been dried and rewet fracture more readily than fully saturated wet fibers.

III. Initial test results from treatments of never-dried webs

50% of furnish,* given by basis weight	Fiber loss, %		Wet web tensile strength, kN/m	
	Test 1	Test 2	MD	CD
Southern pine pulp				
47 g/m²	5	7	0.51	0.37
81 g/m²	6	8	1.12	0.87
Eucalyptus pulp				
53 g/m²	6	9	0.42	0.36
78 g/m²	6	10	0.61	0.61
Cotton linter				
48 g/m²	3	5	0.63	0.64
80 g/m²	4	6	1.46	1.40
Manilla pulp				
46 g/m²	3	4	0.74	0.77
76 g/m²	3	4	1.38	1.38

*The other 50% was polyester in each case.

Future work

We are planning further experiments to examine the effect of fiber treatment on the cellulose fiber portion of the composition, by using controlled refining to enhance hydration. The effects of hydroentanglement on man-made fibers will also be examined for such parameters as fiber breakage and damage.

We will also look into using wet forming to produce precursor webs containing 6-12 mm of glass carbon and polyimide fibers, in conjunction with low levels of pretreated cellulose. The goal would be to provide a carrier system for longer, high-performance materials, with the option of subsequent removal from the entangled web.

In addition, we will study the production of composites based on wet-formed precursors combined with materials from other web process technologies. These materials include melt-blown films, scrim-air-formed nonwovens, and low-density pulp.

Preliminary conclusions

Economically, the costs of the fiber components in a precursor web are significant. Using cellulose fibers or sophisticated forms of cellulose pulp is of considerable economic benefit.

If this simple cost advantage can be combined with other technological and performance benefits and the negative factors can be further minimized, there is no doubt that web-formed precursor webs with off-line entanglement, drawing on a wide range of precursor web technologies, could prove to be an economic and efficient manufacturing system.

One of the key factors will be the ability to form, reel, and transport appropriate wet-formed precursors.□

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