Utilizing Cellulon® cellulosic fiber for binding in nonwoven applications

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ABSTRACT

Cellulon® is a new cellulosic fiber produced by agitated aerobic bacterial fermentation. It has a highly intertwined and reticulated structure. The fibers are approximately 0.1 µm wide and of indeterminate length, providing a tremendous surface area. Bacterial cellulose can be effectively used as a safe, natural, formaldehyde-free binder in specialty paper and nonwoven applications. A special advantage of using bacterial cellulose as a binder is that it allows for cellulose-containing nonwovens to be recycled in the same way as recovered paper. The tensile strength of both wet and dry sheets increases as the concentration of bacterial cellulose increases.

Application:

Bacterial cellulose performs well in many applications and is suitable for use in a broad spectrum of products, including nonwovens for medical and hygiene applications, specialty wet-laid papers, and filtration material.

CELLULON® BACTERIAL CELLULOSE is a unique form of cellulose produced in an agitated culture by a selected strain of *Acetobacter*. The basic process involves supplying the necessary carbon and nitrogen sources, other required nutrients, water, and oxygen to the inoculum culture. When the cellulose content in the fermentor reaches the desired level, the cellulose is separated and processed to remove the cells and residual fermentor broth. The process used destroys any viable cells that may be entangled within the cellulose matrix. The resulting product is then pressed to a preferred solids content, generally treated with sorbic acid as a biocide, and packaged for use.

Bacterial cellulose is a functional product, adding value in selected markets. It is a novel polysaccharide produced using a biotechnology process and renewable resources. It possesses a unique fibrous network composed of extremely fine reticulated fibers, which impart a very high surface area with a large void volume. Bacterial cellulose has been found to have a high affinity to water, an attribute that can be modified by certain chemical treatments of the fiber. It is this high surface area and its natural proclivity for hydrogen binding that make bacterial cellulose useful as a binder, especially in wet-laid nonwoven applications, but also as an agglomerant for minerals or as a retention aid in nonwoven and paper manufacture.

The purpose of this paper is to illustrate the utility and functionality of bacterial cellulose as a binder. The effect of bacterial cellulose on both wet and dry tensile strength will be explored, and potential applications will be discussed.

PRODUCT HISTORY

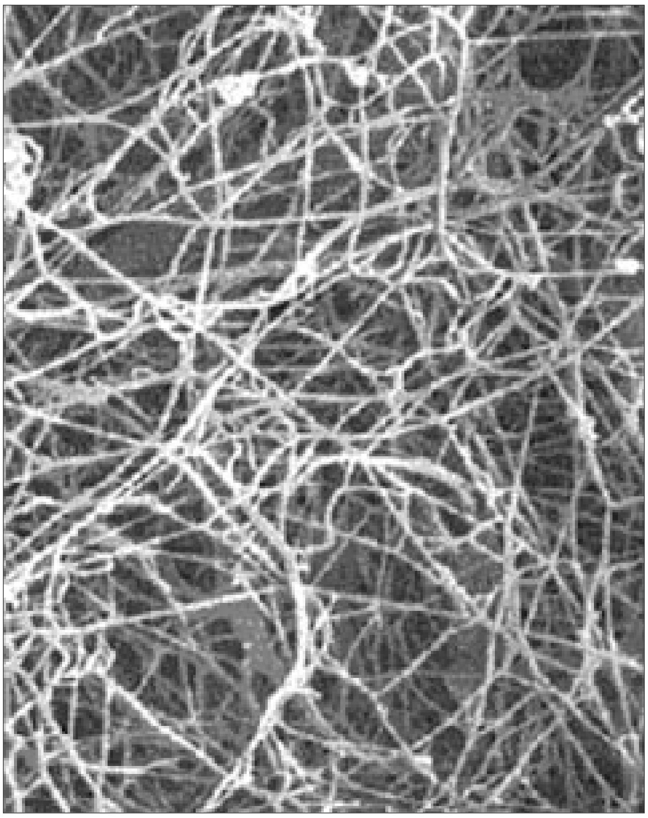
Cellulon® is the registered trademark for the fermentation product made by agitated culture of *Acetobacter* strains and is sometimes referred to as *reticulated bacterial cellulose.* The product was acquired by Monsanto from Weyerhaeuser Co. in 1995. Weyerhaeuser and Cetus developed this bacterial cellulose through a joint research and development partnership, which was established to assess commercial prospects for production of cellulose by a bacterial source. The elegant pioneering work describing the extrusion and assembly of cellulose chains elaborated by Professors Malcolm Brown, Moshe Benziman, and Candace Haigler accelerated the understanding of cellulose formation and biochemistry.

It had been demonstrated that cellulose-producing bacteria did not tolerate agitation. A major milestone of the early research was the selection of a strain of *Acetobacter*, which retained its ability to manufacture cellulose under agitated fermentation. Media and process optimization resulted in dramatic increases in the yield of cellulose. Monsanto has continued to improve the process and is now producing bacterial cellulose at the commercial scale.

PRODUCT MORPHOLOGY

The scanning electron micrograph shown in **Fig. 1** represents the structure of the product made in an agitated culture. The fibers are greatly entangled in a reticulated network, from which the name *reticulated bacterial cellulose* was coined. It is apparent that the fiber strands of the cellulose produced under these conditions are extremely thin—about 0.1 µm in diameter. To put this in perspective, single wood pulp fiber 30 µm wide would fill the entire micrograph. The width of cotton fiber is approximately 15 µm.

It has been difficult to define a discrete length of a single bacterial cellulose fiber because of the reticulated network that it readily forms. It is generally believed that the bacterial-derived cellulose grown under agitated cultures is indeterminate in length. This is in contrast to softwood pulp fiber, with a fiber length of 2–5 mm, or cotton fiber, with a length of 25 mm.



1. A fully activated Cellulon® dispersion viewed with scanning electron microscopy

TNP, %	SBK, %	Cellulon, %	Tensile index, N·m/g	Tear index, mN·m²/g
100	0	0	38.2	7.1
85	15	0	38.2	10.1
84	15	1	41.9	10.4
83	15	2	44.4	10.3
80	15	5	46.1	9.5

I. Properties of TNP/SBK/Cellulon® blends

Cellulon, %	Basis wt., g/m²	TENSILE INDEX, N·m/g Dry	Wet
0	100	0.03	0.100
1	101	3.74	0.388
2	102	12.71	0.601
5	105	23.32	0.931

II. Rayon sheet with Cellulon® binder

Cellulon, %	Basis wt., g/m²	TENSILE INDEX, N·m/g Dry	Wet
0	109	3.21	0.501
1	108	7.28	0.493
2	108	9.07	0.563
5	107	13.63	0.804

III. Kevlar® sheet with Cellulon® binder

The network structure and fine fiber diameters lead to a high surface area, which has been estimated to be two orders of magnitude greater than that of softwood pulp fibers. Bacterial cellulose has also demonstrated a large capacity to hold water. This is probably attributable to the large void volume within the matrix coupled with the hydrophilic nature of the cellulose surface. Free-draining water loss is minimized at usage levels of 6%.

Bacterial cellulose can be used as a binding agent for nonwoven fabrics in place of or in conjunction with the various resins commonly used for binding. Among the properties controlled by bacterial cellulose are strength, porosity, hydrophilicity, and hand or feel of the final product. Suitable fibers include all those currently used for nonwoven fabrics, such as rayon, nylons, polyesters, and wood fibers, as well as materials used in other nonwoven applications, such as glass fibers, carbon fibers, Kevlar®, etc.

EXPERIMENTAL

Handsheets using bacterial cellulose as the binder were made from the following: thermomechanical pulp and kraft pulps, rayon, Kevlar, wood pulp and polyester, and glass fiber. Bacterial cellulose was dispersed in each of the samples using a standard laboratory British disintegrator with 2 L of water for 15 min (1800 counts). The levels of bacterial cellulose used were 0, 1, 2, and 5% wt/wt (weight of bacterial cellulose/total fiber weight, dry basis). The resultant fiber slurry was sheeted on a 200-mesh wire screen in a semi-automatic sheet mold according to TAPPI T 205 om-81.

Each sheet was drained, autocouched with three blotter layers, and then dried in a platen dryer at 105°C. The basis weight for each of the resulting sheets was determined, and the tensile strength of each sample was measured. The tensile index of each sheet was determined using a horizontal sample jig attached to a constant strain rate device (Instron 1122). Wet tensile strength was determined by spraying water on the samples in the jig until saturated, waiting 30 seconds, and then exerting tension on the sample.

RESULTS AND DISCUSSION

Binding of kraft and thermomechanical pulps

Bacterial cellulose was added to a mixture of thermomechanical newsprint pulp (TNP) with 15% unrefined, semi-bleached softwood kraft pulp (SBK). The thermomechanical pulp was refined to a freeness of 74 mL CSF, and the kraft pulp was refined to 659 mL CSF. The resulting sheets were tested for tensile and tear strengths; the test results are shown in **Table I.**

The data show the contribution of bacterial cellulose to tensile strength improvement without significantly penalizing tear strength.

Binding of rayon and Kevlar fibers

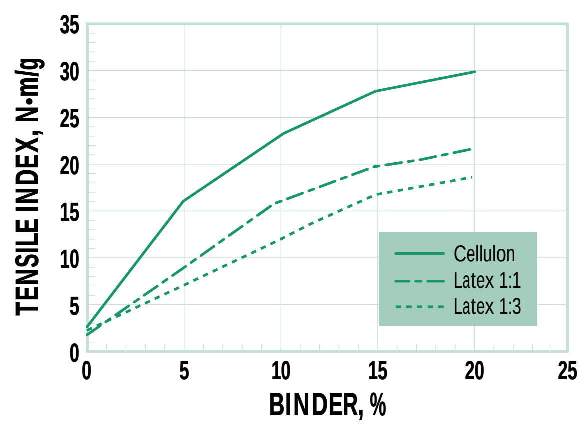
Bacterial cellulose was used as the binder in sheets composed of rayon or Kevlar. The rayon fibers were

Polyester, %	Wood pulp, %	Cellulon, %	Tensile index, N·m/g	Tear index, mN·m²/g
50	50	0	1.1	6.4
25	75	0	2.3	7.7
30	50	20	27.3	53.7
40	40	20	22.6	>55
45	45	10	21.8	>55
30	60	10	20.6	41.3
15	80	5	14.4	25.0
15	75	10	20.4	31.3
10	70	20	27.5	27.2
0	100	0	3.8	3.9

IV. Properties of Cellulon®-bonded nonwoven fabric

Polyester, %	Wood pulp, %	Latex, %	Tensile index, N·m/g	Tear index, mN·m²/g
45	45	10	14.7	>55
40	40	20	19.7	>55
35	35	30	25.2	>55
30	50	20	23.3	>55
23	67	10	11.8	38.3
20	60	10	16.5	40.7

V. Latex-bonded nonwoven sheets



2. The effect of binder concentration on the tensile index of various polyester–wood pulp nonwovens

approximately 3 mm in length and of 1.5 denier, while the Kevlar fibers were approximately 2 mm in length. The wet and dry tensile strengths of the rayon and the Kevlar sheets were measured; the results are presented in **Tables II and III,** respectively.

Significant improvement in dry tensile strength was observed as the bacterial cellulose content of the sheets increased. The improvement in the wet tensile strength was more pronounced for the rayon sheets than for the Kevlar sheets, although wet tensile strength improvement was demonstrated for both samples.

Binding of polyester and wood pulp fibers with Cellulon

Various amounts of wood pulp and bacterial cellulose were dispersed in a standard laboratory disintegrator, followed by addition of the polyester fiber and a nonionic surfactant to help disperse the fibers. The slurry was transferred to a TAPPI sheet mold, and handsheets were made as previously described. The resulting sheets were then tested for tensile and tear strength. The compositions and pertinent physical properties are given in **Table IV.**

The use of bacterial cellulose contributed significant tear and tensile strength to the fabric. The efficiency of the bacterial cellulose can be seen by comparing these samples with samples that were conventionally bonded by resin. Dried wet-formed sheets were placed on polyethylene sheeting and sprayed with a sufficient amount of a latex emulsion to give the desired add-on. The latex used was soft, heat-reactive, acrylic material, diluted to 6% active before spraying. The sheets were dried overnight and placed in an oven at 150°C for 30 min to cure the latex. Sheets were conditioned and tested as previously described; the results are reported in **Table V.**

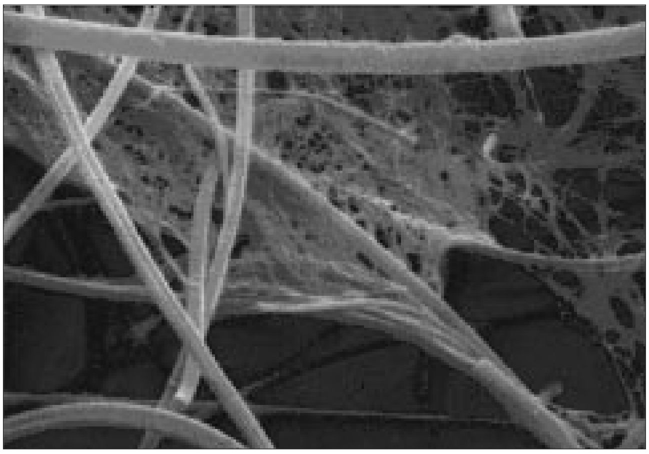
Bacterial cellulose is at least equivalent to the latex binder in contributing to tear strength. Bacterial cellulose is superior to the latex in all cases in its contribution to tensile strength. Furthermore, tensile strength of the products made using bacterial cellulose as a binder appears to be essentially insensitive to the ratio of the polyester fiber to the wood pulp. This is quite in contrast to the use of any given concentration of latex binder, where tensile strength decreases as the ratio of wood pulp to polyester is increased.

This effect on tensile strength is apparent when the data of Tables IV and V are plotted (see **Fig. 2**). All of the points plotted for bacterial cellulose binder fall closely on the upper curve, even over the wide range of ratios of polyester to wood pulp (1:1 to 1:6.7). The two ratios of polyester to wood pulp used with the latex binder fall on individual curves.

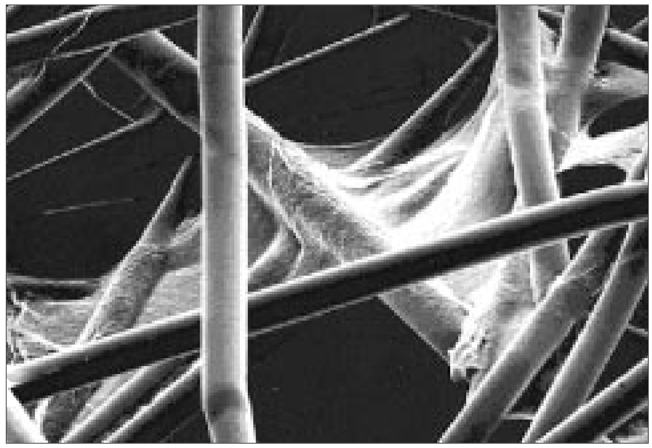
This phenomenon is important because it indicates that much lower usage levels of the expensive polyester fiber would be acceptable when using bacterial cellulose as the binder. Expressed from the standpoint of binder efficiency, 10% bacterial cellulose is equivalent in both tear and tensile strength contribution to 20–30% latex. It should be noted that resin-bonded materials are far superior to those bonded with bacterial cellulose alone when retention of tensile strength under wet conditions is a critical property. This can be addressed by using a combination of bacterial cellulose and resin binders.

Mechanism of binding

The binding functionality can best be explained by examining SEM micrographs. **Figure 3** illustrates a nonwoven product comprised of 95% glass



3. SEM micrograph of nonwoven sheet composed of 95% glass fiber and 5% Cellulon®. Magnification=8500x.



4. SEM micrograph of nonwoven sheet composed of 90% polyester fiber and 10% Cellulon®. Magnification=3500x.

5. SEM micrograph of clay particles agglomerated with 0.05% Cellulon® fiber. Magnification=3500x.

fiber/5% bacterial cellulose, and **Fig. 4** shows 90% polyester/10% bacterial cellulose. The magnification differs between the two micrographs as indicated. Bacterial cellulose acts as a binding and support matrix for the other fibers. The mechanism of binding is believed to be primarily due to physical entanglement, with the bacterial cellulose reticulated network distributed over and adhering to the surfaces of the substrate fragments. There does not appear to be any substantial degree of penetration of the cellulose fibers into the structure of the substrate. The high surface area and the degree to which hydrogen bonding occurs on the bacterial cellulose surface may facilitate this interaction.

Bacterial cellulose has been shown to effectively bind substrates of sizes ranging from microscopic (such as cellular wood fibers or bacteria) to several centimeters in length (such as multicellular wood fibers). It has also been demonstrated that bacterial cellulose can be used to bind natural, chemically, or physically treated wood fibers; plant-derived fibers and fragments such as bagasse, hemp, etc.; synthetic fibers and fragments such as Kevlar, rayon, and polyester; and mineral ores such as clay, TiO_2, and fly ash. This can be seen in the SEM micrograph of clay agglomerated with bacterial cellulose shown in **Fig. 5.** This photo shows the result after blending the fine clay particles with only 0.05% (500 g/metric ton of clay) bacterial cellulose fiber followed by drying and grinding. This agglomeration effectively increases the average particle size of the clay.

Similar results have been obtained with very fine particles such as carbon black and fly ash. In all cases, the reticulated structure of bacterial cellulose appears to be responsible for its enhanced binding attributes.

CONCLUSIONS

We have demonstrated that Cellulon® bacterial cellulose can be used successfully as a binder in nonwoven applications. The material, which can be bound into a matrix or composite using bacterial cellulose, covers the size range from submicron to centimeter in length. Bacterial cellulose imparts excellent tensile strength when used as a binder. It can be used by itself or in conjunction with the various resins that are currently used for binding. The mechanism of binding is believed to be primarily due to physical entanglement. TJ

KEYWORDS

Adhesives, bacteria, binders, cellulose fibers, fabric, fiber networks, mechanical properties, microorganisms, natural fibers, nonwovens, recyclable materials, tensile properties, tensile strength.

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