10
Biodegradable nonwovens

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10.1 Introduction

Nonwoven fabrics are flat, porous sheets or web structures that are made directly from separate fibers or from molten plastics or from plastic films by entangling fibers or filaments mechanically, thermally or chemically. Nonwovens can be produced from both natural and synthetic fibers or directly from polymers by a variety of techniques that involve web formation and bonding. Different polymers/fibers are more suited for one process than the other. All of the different techniques available for web formation and bonding are discussed in sufficient detail.

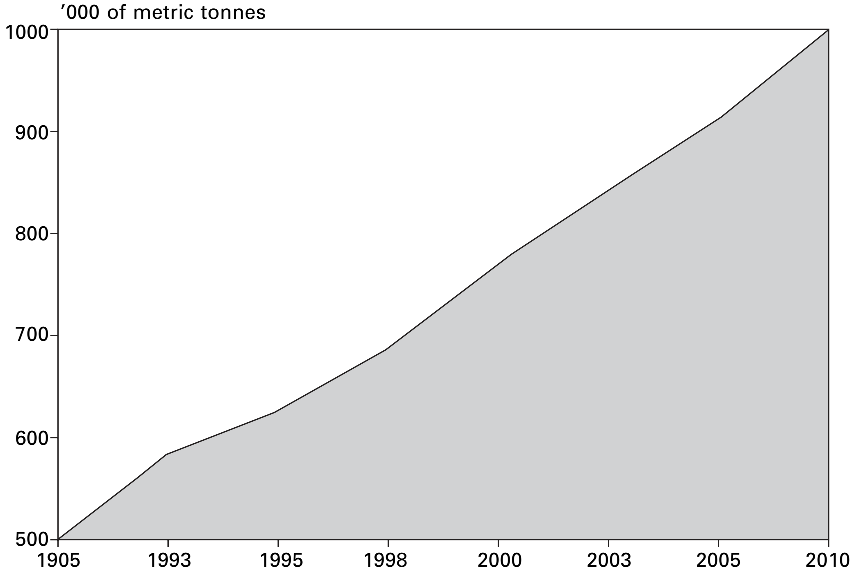
Nonwovens are the fastest growing sectors of textile materials, and they continue to grow all over the world. A significantly large share of these are used as single use, or short-life products, leading to disposability related problems; biodegradable or compostable nonwovens are the answer to the sustainability issues, especially in the long run. Studies done on processing, structure and properties of the nonwovens produced by different techniques from a variety of biodegradable polymers and fibers are discussed. Although the techniques used are similar to the ones used for other commonly used polymers/fibers such as polypropylene, polyester and cellulosics, some specific issues need to be addressed with newer polymer/fiber candidates.

Since most of the biodegradable polymers and fibers are discussed in detail in other chapters, only a brief overview of the materials used in biodegradable nonwovens is provided, with detailed discussions about the processing of these materials into nonwoven webs. Structure and properties of such nonwovens from different biodegradable materials, especially with reference to their processing and performance are detailed. Included in the discussion are the fast growing applications of these nonwovens. As these fabrics are becoming more and more important, there is a lot of information and update one can obtain through important books, websites and professional organizations listed in this chapter.

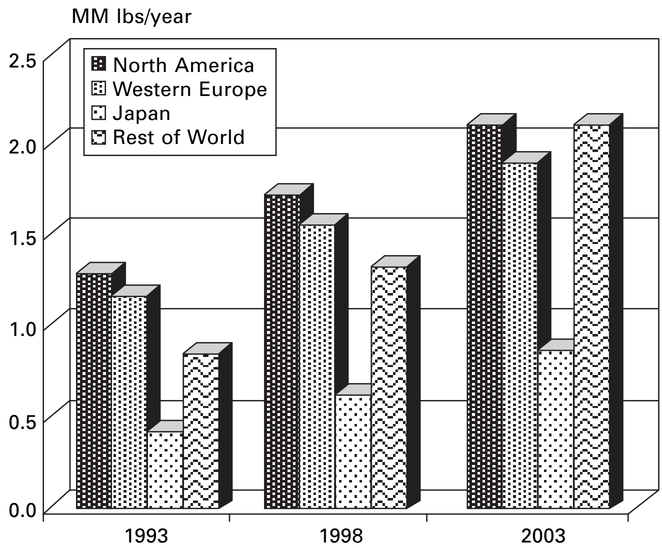
10.2 Nonwoven fabrics

Unlike traditional textiles, nonwoven fabrics are not manufactured by the traditional processes of weaving or knitting, and converting of fibers to yarns is not required. Both natural and synthetic fibers, organic and inorganic, can be used for nonwoven fabrics. The fibers in these structures may be staple or continuous, or be formed *in situ*, and may be directionally or randomly oriented, depending on the nature of their production process. According to INDA [1], the association of the nonwovens fabrics industry: 'Nonwovens are a sheet, web, or batt of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, and that are bonded to each other by any of several means.' European nonwovens association EDANA defines: 'Nonwoven as a manufactured sheet, web or batt of directionally or randomly oriented fibers, bonded by friction, and/or cohesion and/or adhesion, excluding paper or products which are woven, knitted, tufted stitch bonded incorporating binding yarns or filaments, or felted by wet milling, whether or not additionally needled. The fibers may be of natural or man-made origin. They may be staple or continuous or be formed *in situ*.'

Nonwoven fabrics demonstrate specific characteristics such as strength, stretch, resilience, absorbency, liquid repellency, softness, flame-retardancy, cushioning, washability, filtering, bacterial barrier and sterility. Nonwoven fabrics can be used in a wide variety of applications, which may be limited life, single-use fabrics as disposable materials or durable fabrics for automotive and civil engineering applications [2, 3]. Demand for nonwoven materials in the US is expected to increase by 3.9% per year to nearly $5 billion in 2007. Nonwoven growth trend in the world and the growth trend for North American nonwovens market are shown in Figs 10.1 and 10.2. This increasing market share will be driven by the strong growth in many key disposable markets such as adult incontinence products, filters, and protective apparel, and key non-disposable markets such as geotextiles and battery separators. Disposable markets are still the majority of nonwoven demand in 2002, which account for a 64% share (Fig. 10.3) [4]. Disposable consumer products, which primarily include baby diapers, adult incontinence and feminine hygiene products, and wipes, were the largest market for nonwovens in 2002 [5]. Based on the data that is available, continued growth in nonwovens is more in the disposables area and the share of the short-life nonwovens is going to remain significantly large. Also, looking at the distribution of durables and disposables in terms of yardage or volume, the disposable share is four-fifths of the total nonwovens, making them much more visible in the waste stream. Considering the fact that large share of these important and growing materials are throw-away products, it is important that issues related to their disposal be carefully addressed.

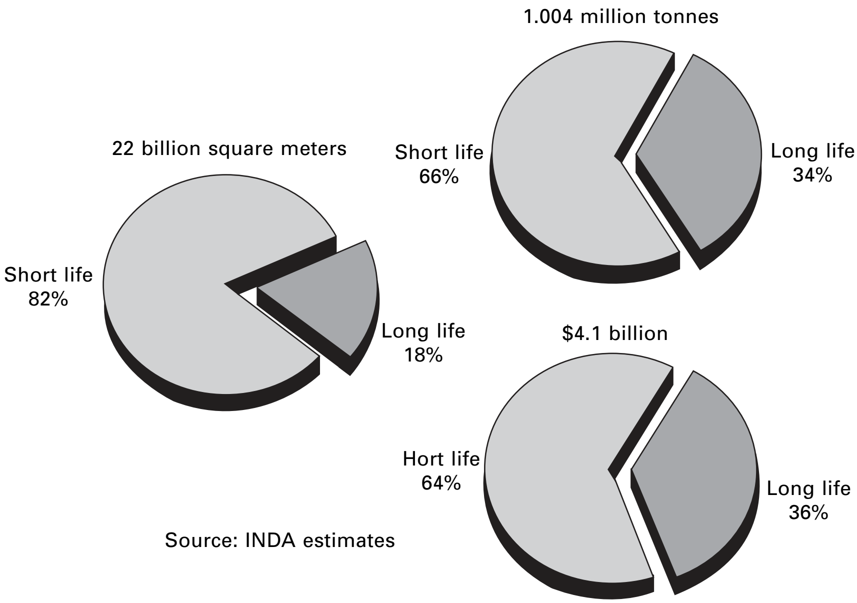


10.1 North American nonwovens market [4].



10.2 Trend in world nonwovens production [4].

Nonwovens are used almost everywhere, in agriculture, construction, military, clothing, home furnishing, travel and leisure, health care, personal care and household applications. Of these many applications that continue to grow, more than two-thirds of them are disposables, mostly of single-use type.



10.3 North American nonwovens volume and sales [4].

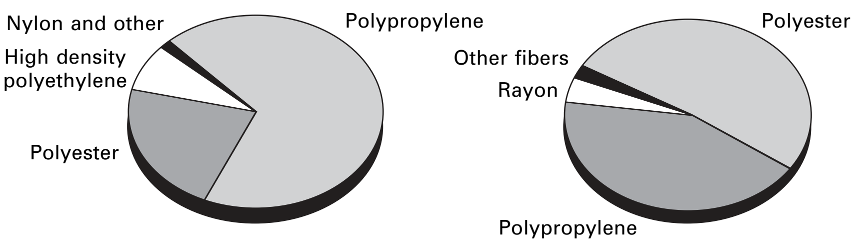
The environmental impact of disposable products is becoming a major concern throughout the world in recent years [6–7]. These disposable products are usually produced from traditional thermoplastic resins, such as polypropylene (PP), polyethylene (PE), polyester (PET), polyamide (PA), polycarbonate (PC), which are not biodegradable. However, due to increasing environmental consciousness and demands of legislative authorities, the manufacture, use and removal of products made of such traditional polymers are considered more critically. The remedy to this problem could be found in the development of substitute products based on biodegradable, and ideally from natural and renewable materials.

Natural fibers, such as cotton, kenaf, coir, jute, flax, sisal, hemp, and wood, etc., become the first choice due to their biodegradability. Some synthetic biodegradable fibers have also been used for nonwoven applications, including cellulose esters such as cellulose acetate, rayon, lyocell, etc., polyesters such as poly(lactic acid) (PLA), poly(caprolactone) (PCL), poly(hydroxybutyrate) (PHB), poly(hydroxybutyrate-co-valerate) (PHBV), Biomax, Biopol, polytetramethylene adipate-co-terephthalate (PTAT), etc., and water solubles such as poly(vinyl alcohol) (PVA), etc.

Thus the target for biodegradable nonwovens is to replace synthetic fibers with biodegradable fibers in the disposable nonwovens. One group of disposable nonwovens is the wet laid pulp/polyester spunlaced fabrics mainly for industrial and professional wipe products. Another group of disposable nonwovens is household and hygienic wipes, which are spunbonded or dry laid and then chemically or thermally bonded.

10.3 Fiber consumption in nonwovens

Fibers are the basic element of nonwovens; world consumption of fibers in nonwoven production is 63% polypropylene, 23% polyester, 8% viscose rayon, 2% acrylic, 1.5% polyamide and 3% other high performance fibers [8]. The data in Fig. 10.4 shows the market share of important polymers and fibers in the nonwovens market. Manufacturers of nonwoven products can make use of almost any kind of fibers. These include traditional textile fibers, as well as recently developed hi-tech fibers. Future advancements will be in bicomponent fibers, micro-fibers (split bicomponent fibers or meltblown nonwovens), nano-fibers, biodegradable fibers, super-absorbent fibers and high performance fibers. The selection of raw fibers, to a considerable degree, determines the properties of the final nonwoven products. The selection of fibers also depends on customer requirement, cost, processability, changes of properties because of web formation and consolidation. The fibers can be in the form of filament, staple fiber or even yarn.



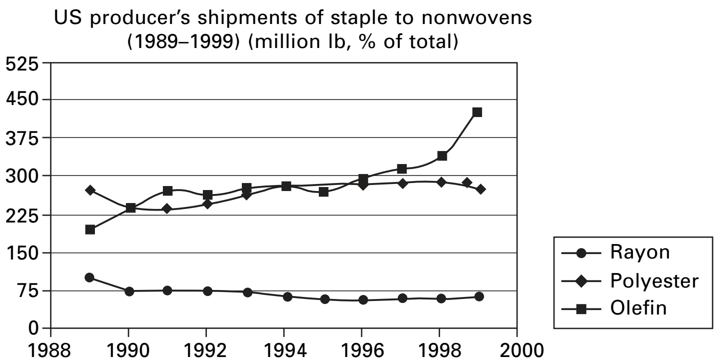
10.4 Consumption of polymers and fiber types in nonwovens [4].

Many different fiber types are used in the formation of nonwovens:

- *Traditional textile fibers*:
  - PET, polyolefin (PP/PE), nylon, cotton, rayon, wool, lyocell, modacrylic.
- *Advanced fibers*:
  - aramid (Nomex/Kevlar);
  - conductive nylon;
  - bicomponents (side-by-side, sheath-core, segmented pie, and islands-in-the-sea);
  - melamine (heat and flame resistant);
  - hollow fibers (polyetherketone, polyaniline);
  - Spandex fibers (polyether)
  - fusible co-PET fiber;
  - nylon 6 support/matrix fiber;

  – glass micro-fiber;
  – chlorofiber;
  – antibacterial fiber;
  – stainless steel;
  – rubber thread;
  – poly(tetrafluoroethylene) (PTFE);
- *Nanofibers*:
  – carbon nanotubes;
  – electrospun polymeric nanofibers

However, the major players continue to be polyolefins and polyesters, with rayons having a visible third place. As can be seen from the recent trend (Fig. 10.5), the rayon share is going down and share of polyolefins is continuing to increase.



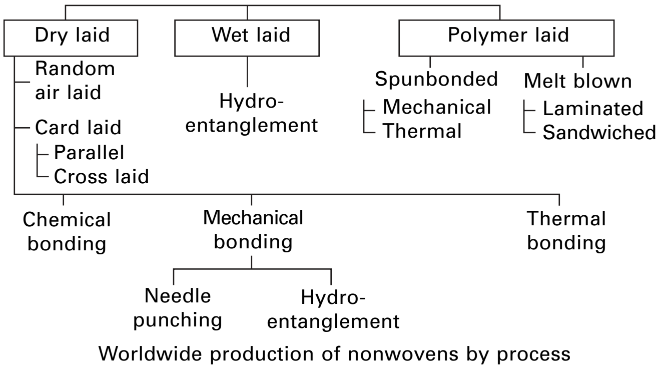
10.5 Trend in US shipment of nonwovens (4).

10.4 Web formation methods

The web formation in nonwoven production is a critical part of end-use product performance. Three basic methods used to form a web are: dry laid; wet laid; and polymer laid (spunlaid and melt blown). Webs, other than spunlaid, have little strength in their unbonded form. The web must therefore be consolidated in some way. There are three basic types of bonding: chemical; thermal; and mechanical. The nonwoven formation methods are summarized in Fig. 10.6.

10.4.1 Dry laid

In the dry laid process, the conventional staple fibers are used, which are usually 12 to 200 mm or longer. The fibrous web is prepared using the classical textile carding machine or air laying machine to separate and orient



10.6 Nonwoven web formation methods (from ref. 3).

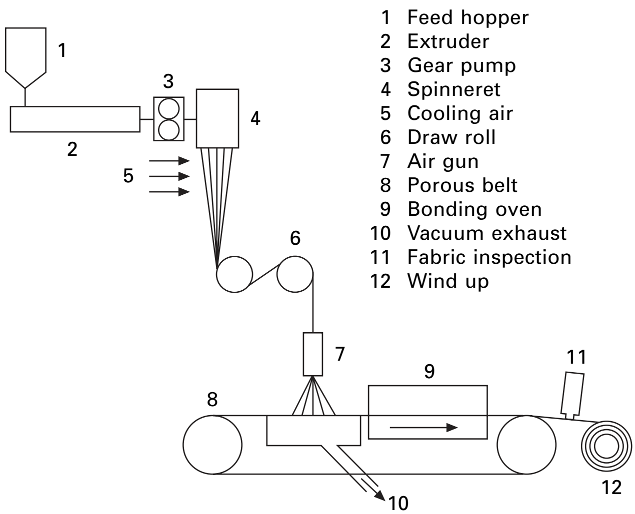
the fiber mechanically. Carding is the most common process to produce nonwoven fabrics from staple fibers. The objective of carding is to separate the fiber stock into individual fibers with minimum fiber breakage. Thus, the carding process consists of opening and blending of different species of fibers thoroughly; carding is performed by the mechanical action in which the fibers are held by one surface while the other surface combs the fibers, causing the separation of individual fibers. In a normal carding process, the fibers are more oriented along machine direction than cross-direction. More random web structures can be obtained by cross-lapping, centrifugal dynamic random card system, or by using aerodynamic web formation (air lay) method [7]. The carded or air laid web usually has a basis weight ranging from 1 to 90 ounces per square yard. Typical end uses for dry laid nonwoven fabrics are the fabrics for carpet backing, interlinings for garments, apparel and upholstery backings, filter media, diaper coverstock, wipes, and personal hygiene products.

10.4.2 Wet laid

Wet laid nonwovens are webs made by a modified papermaking process. First, the fibers are mixed with chemicals and suspended in water to make the slurry. Then, specialized paper machines are used to drain the water off the fibers to form a uniform sheet of material, which is then bonded and dried. Thus, three steps are needed for the wet laid process, the swelling and dispersion of the fiber in water, transporting the suspension onto a continuous traveling screen to form the continuous web, and drying and bonding of the web [9]. Short fibers, which are usually less than 10 mm, are needed for the wet laid process and the resulting fabric has a basis weight ranging from 10 to 540 g m^{-2}. The wet laid process has advantages of high productivity, control of orientation of properties, and high uniformity at low basis weight when compared with the air laid process. Typical applications for wet laid nonwovens include tea bags, wipes, surgical gowns and drapes, towels etc. [7].

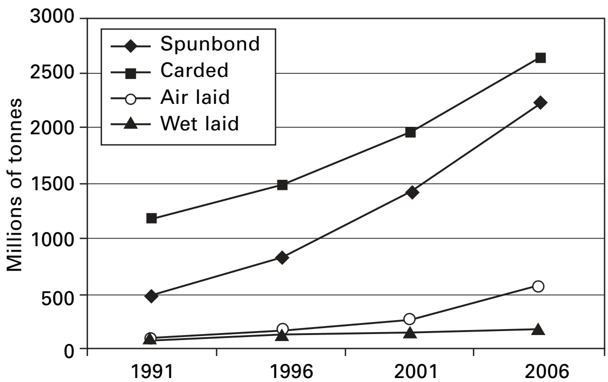
10.4.3 Spunbonded

Spunbonding is a one-step process, which involves polymer melting, filament extrusion, drawing, laydown and bonding of the web to impart strength, cohesiveness and integrity to it. A schematic of a spunbonding process is shown in Fig. 10.7 [9]. The spinning process is similar to the production of continuous filament yarns and similar extrusion conditions are used for a given polymer. Fibers are formed as the molten polymer exits the spinnerets and are quenched by cool air. Unlike in the typical fiber spinning process, there is no positive take-up and fibers are directly deposited on a moving collector to form a web. Before deposition on a moving belt or screen, the individual filaments must be attenuated to orient molecular chains within the fibers to increase fiber strength and decrease extensibility by rapidly stretching the plastic fibers immediately after exiting the spinneret either mechanically or pneumatically. Then the web is formed by the pneumatic deposition of the filament bundles onto the moving belt. The fibers have to be distributed on the belt using some type of randomization so that a fairly uniform random web is formed. The formed webs are bonded either by mechanical, chemical, or thermal method depending on the ultimate fabric applications [10]. Of the different options, thermal point bonding is the commercially popular method,



10.7 Schematic of a spunbonding process [10].

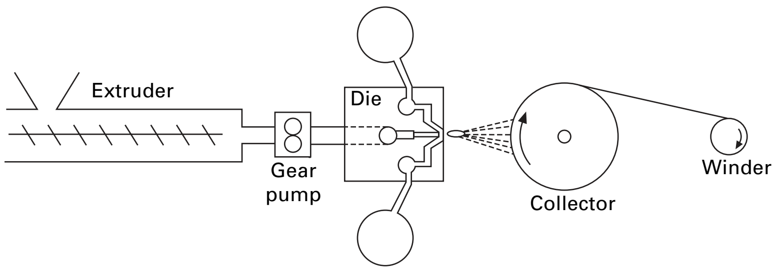
wherein the bond area is about 15%. At these bond points fiber surfaces are partially melted to form fusion between neighboring fibers, thereby imparting strength to the webs. Today spunbonded fabrics have been widely used throughout the automobile as backing for tufted automobile floor carpets, trim parts, trunkliners, interior door panel, and seat covers, etc. For the civil engineering applications, spunbond fabrics have been applied for erosion control, revetment protection, railroad beds stabilization, canal and reservoir lining protection, highway and airfield black top cracking prevention, roofing, etc. [11]. Spunbonded fabrics have also been widely used in sanitary, medical and packaging industries [12]. Spunbonding is one of the fastest growing processes as indicated in Fig. 10.8 [13].



10.8 Worldwide nonwoven production by process [13].

10.4.4 Meltblown

Melt blowing is one of the most popular processes to make super-fine fibers on the micron or sub-micron scale. In a melt blowing process a thermoplastic polymer is extruded through an extruder die which is rapidly attenuated by the hot air stream to form the extremely fine diameter fibers. The attenuated fibers are then blown by high-velocity air to a collector screen to form a fine fiberd, self-bonded web. The combination of fiber entanglement and fiber-to-fiber bonding generally provides enough web cohesion so that the web can be used without further bonding. A schematic of a melt blowing process is shown in Fig. 10.9 [7]. Melt blown fibers generally have diameters in the range of 2 to 7 μm, although they may be as small as 0.1 μm and as large as 30 μm. Due to the large fiber surface area of the melt blown fabrics, they are used in filtration, insulation and liquid absorption applications. Because of the simplicity of the process, any thermoplastic fiber can be melt blown. However, the polymer should have very low melt viscosity, and it is an energy consuming process.



10.9 Schematic of a melt blowing process.

10.5 Web bonding techniques

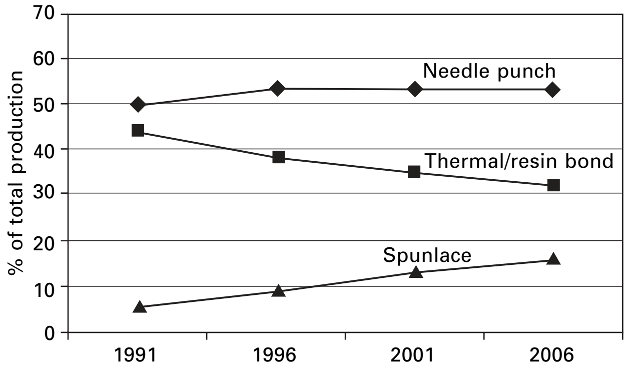
The web bonding techniques can be generally classified into three categories, mechanical, chemical, and thermal bonding, depending on the ultimate fabric applications and/or on the web formation method. Sometimes, in order to achieve products with certain properties, a combination of different bonding methods is applied.

10.5.1 Mechanical bonding

Mechanical bonding can be further classified as needle punching, stitching, and spunlacing (hydraulic entangling). Needle punching is a process of bonding nonwoven web structures by mechanically interlocking the fibers through the web via the barbed needles. It is the only bonding method suitable for heavyweight nonwoven fabric bonding. The needle-punched fabrics are extensible, bulky, conformable, distortable and extremely absorbent. Both dry laid and polymer laid webs can be needle punched. Needle punched fabrics have been used as carpet backing fabrics, automobile carpets and headliners, blankets, and geotextile fabrics [7]. Stitch bonding is the process of bonding a web by using stitching yarns, filaments, fibers, or just the stitching needles themselves to do the bonding. Stitch bonded fabrics have taken the place of woven goods in many applications such as decorative fabrics for home furnishing, shoe fabrics, backing fabrics for artificial leather, etc. Spunlacing is a process of entangling individual fibers with each other by using high-pressure water jets, which cause the fibers to migrate and entangle. Spunlaced fabrics can be used as wipes, medical gowns, dust cloths, etc. [7]. The popularity of spunlaced fabrics is increasing and the share of this process continues to climb (Fig. 10.10).

10.5.2 Chemical bonding

Bonding a web by means of a chemical is one of the most common methods of bonding. The polymer latex or a polymer solution is applied to the web

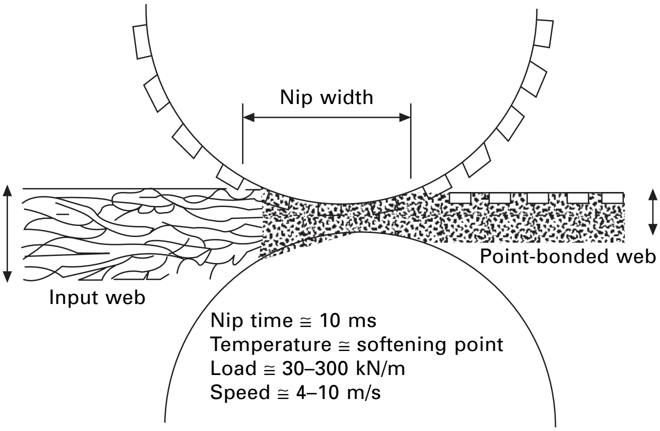


10.10 Market share by weight from different processes during 1991–2006 [13].

and then cured thermally to obtain bonding. Several methods are used to apply the polymer latex/solution and these include saturation bonding, spray bonding, print bonding, and foam bonding. Chemically bonded fabrics have been widely used as wipes and towels, apparel interlinings, automotive trim, filter media, etc. [14]. Use of the right chemical binder depending on the fiber and the intended application is important since the binder stays in the fabric. Also, environmental issues while applying or curing the binders also need to be considered.

10.5.3 Thermal bonding

Thermal bonding is the process of using heat to bond or stabilize a web structure that consists of a thermoplastic binder. It is the most popular method of bonding used in nonwovens, because of the favorable process economics, the absence of chemical binders, that is, environmentally friendly, the availability of new fibers and machinery, and process and product enhancement. The bonding is achieved by the direct action of heat and pressure by a calender, an oven, a radiant heat source, or an ultrasonic wave source. The thermoplastic binder can be in the form of fiber, web, or powder. There are four methods of thermal bonding. They are hot calendering, oven bonding, ultrasonic bonding, and radiant heat bonding. Hot calendering can be further classified as area or point bond hot calendering, and embossing hot calendering. Among the various types of thermal bonding methods, point bonding using embossing rolls is the most desired method, which is the leading method used by the cover-stock industry for baby diapers. It employs direct contact, with heat and pressure, to produce localized bonding in a nonwoven. Also it adds softness and flexibility to the fabric by the embossing rolls compared with smooth rolls used in area bond hot calendering. A schematic of a point bonding process is illustrated in Fig. 10.11 [15].



10.11 Schematic of a thermal point bonding process [15].

10.6 Technology and relative production rate

One of the reasons for continuing growth of the nonwovens is the high production rates that are possible with the new technologies. The approximate production rates are listed in Table 10.1. Compared to only a few meters per minute possible with the woven or knitted fabrics, nonwovens can be produced at the rate of a few hundred to thousand meters per minute. This high production rate combined with the fact that the intermediate yarn formation is eliminated helps in keeping the cost of nonwovens very low. This low cost of roll goods production has helped the spurt in growth of nonwoven products.

Table 10.1 Fabric production rates from different technologies

Technology	Relative production rate (m/min)
Weaving	1–6
Knitting	3–16
Nonwovens – web forming:	
– Carding	120–400
– Spunbond	200–2000
– Wet-laid	2300
Nonwovens – bonding	
– Stitchbonding	40
– Needling	30–500
– Calendering	2000
– Hot air bonding	5000

10.7 Recent research on biodegradable nonwovens

10.7.1 Natural cellulosic fiber nonwovens

Natural fibers have come a long way; during the past several years, these soft, durable and biodegradable fibers have established a positive and highly regarded name for themselves in numerous nonwovens end use markets because of their reputation for being soft, durable, breathable and coming from renewable resources. These days, traditional natural fibers, including cotton, hemp, flax and jute, have been seeing more demand internationally, while other fibers such as hemp and milkweed are starting to emerge into more developed nonwovens areas. Many manufacturers predict that the use of these fibers will grow, as consumers become more aware of their advantages. In the meantime, manufacturers and university researchers are working on new innovations for all natural fibers. The total production of different natural cellulosic fibers is shown in Table 10.2. Obviously cotton is the most used fiber, again due to its popularity in apparel and other fabrics. Jute, kenaf and flax come next, with the rest of the fibers having only a small share. The cost of these fibers also varies and cotton is the most expensive of this group of fibers (Fig. 10.12) [16]. Although cotton is the most attractive fiber for many applications, the cost is the factor that has limited its growth.

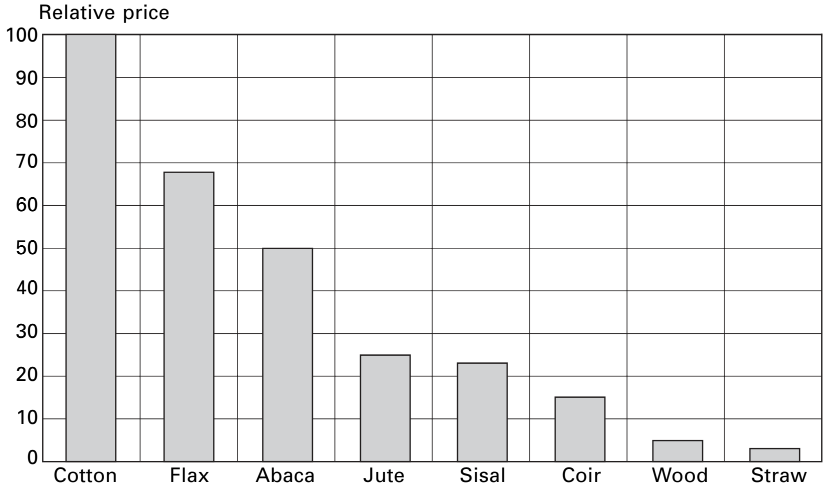
Table 10.2 Commercially important natural fiber sources [16]

Fiber source	World production (10^3 tonnes)	Viable growing regions
Cotton (*Gossypium sp.*)	18,450	E, W
Jute (*Corchorus sp.*)	2300	W
Kenaf (*Hibiscus cannabinus*)	970	E, W
Flax (*Linum usitatissimum*)	830	UK, E, W
Sisal (*Agave sisilana*)	378	W
Roselle (*Hibiscus sabdariffa*)	250	W
Hemp (*Cannabis sativa*)	214	UK, E, W
Coir (*Cocos nucifera*)	100	W
Ramie (*Boehmeria nivea*)	100	W
Abaca (*Musa textiles*)	70	W
Sunn hemp (*Crotalaria juncea*)	70	W

UK = United Kingdom, E = Europe, W = World

10.7.2 Cotton nonwovens

Just about everyone can recognize cotton as a durable, breathable and soft fiber. Perhaps no one recognizes the benefits of cotton as well as Cotton Incorporated, a Cary, NC (USA)-based non-profit organization dedicated to its advancement. Its report, 'Cotton for Nonwovens: A Technical Guide' [17, 18], sheds light on how powerful the name cotton has become. In 2000, the



10.12 Relative cost of fibers from different sources (cotton = 100) [16].

US apparel and home fabrics markets purchased the equivalent of 15.1 million bales of cotton, while the global nonwovens market used the equivalent of 14.7 million bales of fibers; between 1996 and 2000 global consumption of bleached cotton fiber rose by 6%. Cotton's current share of the nonwovens market is 7.8% globally and 2.8% in North America, and in the major consumer markets of North America, Western Europe and Japan, growth of cotton usage in nonwovens is projected at 3–6% per year for the next few years.

A study, conducted by Cotton Incorporated in six cities across the US, tested consumers' perceptions of fiber content in nonwoven products and how these perceptions affected purchasing preferences. One thousand women aged 18 to 49 took part in a study of four product categories: feminine napkins; tampons; baby wipes; and disposable diapers. The women were all shown pictures of well-known brands with and without the Cotton Seal. In each category, the Cotton Seal significantly influenced consumers' purchasing preference. Moreover, 66% of consumers perceived personal care products with this seal to be of higher quality. Fifty-nine percent agreed with the statement, 'I expect to pay more for products with the Cotton Seal', and 57% said they were willing to pay more.

Although cotton in its pure, untouched state is widely used and accepted, cotton can also have special properties applied to it, thereby paving a way for new uses and markets. One of these properties relates to bleaching. Barnhardt Manufacturing Company, Charlotte, NC (USA), produces bleached cotton fibers for carded web products, chemically bonded fabrics, and spunlaced and needled fabrics, with approximately 95% of the company's bleached fibers targeting nonwovens, due to increasing interest of bleached fibers, among nonwoven manufacturers. Cotton, when bleached, is also more aesthetic to consumers who appreciate the snow-white quality of bleached cotton. Also, when a natural fiber such as cotton is dyed, the colors tend to be softer and pastel, unlike synthetic fibers that produce much shinier and usually glare-like effects. Cotton fibers give nonwoven fabrics unique characteristics that synthetic fibers cannot duplicate easily. Synthetic fibers are currently being used more in nonwoven fabrics than cotton because of misconceptions regarding cotton's processability. With improved bleaching techniques and the development of new finish applications, cotton can be processed at speeds comparable to that used with synthetics while providing the superior attributes of cotton to the nonwoven. Most consumer data suggests that consumers prefer cotton fibers.

Additional advantages of cotton and other natural fibers include superior wet strength as well as a quick dry surface, notably in wipes. Bleached cotton fibers have high levels of absorbency and are soft to the touch, breathable and biodegradable. One quickly-growing area, especially throughout Europe and Japan, is spunlaced cotton used for cosmetic wipes and other disposable products; these trends are likely to spread to other markets as well. Consumer demands for cotton are well documented, but because nonwovens are not required to list fiber content in products, consumers often don't know what they are purchasing. There is definitely an opportunity to increase market share by adding the fiber content as being cotton, since there is consumer preference to purchase cotton-containing products [18].

Although cotton, with all its varying attributes, can tend to dominate the natural fibers market, hemp, jute, flax and milkweed are some other examples of fibers that are used not only in nonwovens, but are also growing in popularity in many different applications. As companies become more familiar with the benefits and uses of these fibers, new innovations will be developed in the future.

10.7.3 Hemp

Hemp fibers are not as well known as cotton, but they certainly have proven themselves for Hempline, Delaware, Ontario, Canada. Hempline is a large supplier of hemp fiber to the nonwovens industry, primarily supplying hemp as a reinforcing fiber for substrates. With 50% of the company's sales conducted in the nonwovens industry, Hempline is noticing a rapid increase in demand for its products, especially its reinforcement fibers: 'Hemp fiber has found its way into more vehicles in the past year, and, chances are good that many people have a natural nonwoven fiber product in their car and don't even know it. Hemp fiber has been found to be very cost-effective, with high strength and can be used as an excellent reinforcement fiber for replacing glass fiber, at a much lower price. The increasing commercial availability of hemp fiber and the demand for low cost, high strength fibers has resulted in new applications for hemp, particularly in automotive and construction products.' [19]

Aside from its high strength, hemp has been recognized for its elasticity, ease of processing and recycling. However, there are a few setbacks, the main one being consumers' unfamiliarity with hemp fiber. There is need for consumer education as far as the benefits of hemp are concerned. Key advantages of hemp fiber are its high strength and low cost, and there are many markets still awaiting the use of this fiber as it slowly makes its way into becoming another option for manufacturers. Also, hemp fiber's staple length and strength can be modified according to the needs of the consumer. Although the market is price-conscious, using better qualities of natural fibers results in lower price rejects, reduces downtime on the equipment, minimizes loss of fiber during processing and, overall, makes better economic sense.

10.7.4 Other natural fibers

Another natural fiber increasing its role in the nonwovens industry is milkweed. Milkweed floss is a silky white seed with a resilient hollow tube that looks similar to a straw. It is similar to high quality down and is a hydrophobic, cellulose fiber with a high chemical resistance and the ability to be dyed readily. Some properties milkweed floss can provide nonwovens include super absorbency, softening, hydrophobicity, paper-strength, bulking, self-bonding and tactile-change. Milkweed floss fiber from advanced agricultural production has the ability to compete in nonwoven applications, especially in filtration, absorbent products and thermal and sound insulation products. Natural Fibers Corporation has introduced a 75% recycled cotton and 25% milkweed fiber mattress pad through its subsidiary, Ogallala Comfort Company, Ogallala, NE [19].

Although technology is available to use many of the natural fibers in nonwovens, the industry will have to wait for a number of things to happen, including an improved economic climate, which may possibly change people's willingness to pay for improvements. If anything, this industry is growing internationally, which may force manufacturers and consumers alike to keep up with the competition. Additionally, the natural fiber, particularly cotton, market is currently expanding globally, as it hits uncharted territory around the globe.

10.7.5 Cotton-based fully biodegradable nonwovens

Research on cotton-based nonwovens has been carried out at the University of Tennessee since 1987 by applying different kinds of binder fibers through carding and thermal calendering processes. Cellulose acetate (CA) fiber has first been applied most successfully as the binder fiber since it is thermoplastic, hydrophilic and biodegradable [20–25]. Eastar Bio® GP copolyester unicomponent and bicomponent (Eastar/PP) fibers were further selected as the binder fibers in recent studies [26–30].

Five different kinds of fibers were used for the study. Cotton fiber is the base fiber, and four types of binder fibers, ordinary cellulose acetate (OCA), plasticized cellulose acetate (PCA), Eastar Bio® copolyester unicomponent (Eastar), and Eastar Bio® copolyester bicomponent (Eastar/PP) fibers. The chemical name of Eastar Bio® copolyester is poly(tetramethylene adipate-co-terephthalate) (PTAT). The cotton fiber used in this research as the carrier fiber was supplied by Cotton Incorporated, Cary, NC. The scoured and bleached commodity cotton fiber had a moisture content of 5.2%, a micronaire value of 5.4 and an upper-half-mean fiber length of 24.4 mm. Both the OCA and PCA binder fibers were provided by Celanese Corporation, Charlotte, NC; while the Eastar and Eastar/PP bicomponent binder fibers selected for this study were produced by Eastman Chemical Company, Kingsport, TN. The plasticizer used in PCA binder fiber is triethyl citrate ester ($C_{12}H_{20}O_7$) with a weight concentration around 2%. The bicomponent Eastar/PP has a sheath core structure with Eastar as the sheath and PP as the core. The properties of these selected fibers are listed in Table 10.3.

Table 10.3 Properties of selected fibers

Property	Cotton	OCA	PCA	Eastar	Eastar/PP
Filament density (g cm^{-3})	1.5	1.3	1.3	1.2	1.1
Filament denier (denier)	2.2	1.1	2.9	4.0	4.0
Filament tenacity (g den^{-1})	1.8	1.2	1.3	1.6	2.2
Peak extension (%)	7.8	25.0	50.6	296.1	148.7
Staple length (cm)	2.44[a]	4.32	4.57	2.54	3.81
Crimps per cm	[b]	more	13	[c]	18
Softening temperature (°C)	–	~190	~110	~80	~80[d]
Contact angle (°)	31.90	–	43.04	56.75	63.02

[a] upper-half-mean fiber length; [b] cotton has natural convolution; [c] not measurable; [d] softening temperature of sheath

Processing

The nonwoven fabrics in this research were produced by first carding of cotton and the binder fiber and then thermally bonding the carded webs. The fiber components were prepared by separately opening and then hand mixing of the two fiber types for homogeneity. The fiber blend was then carded to form a web using a modified Hollingsworth card with the conventional flats installed at the licker-end of the machine. The resulting carded webs had the basis weights of about 40 g m^{-2}. After carding, acetone solvent or water dip-nip treatment was applied to some of the carded webs. Then the treated or untreated webs were fed for thermally point-bonding using a Ramisch Kleinewefers 60 cm-wide calender. The embossed roll had a diamond pattern, covering approximately 16.6% of the surface area, i.e., the bonded area was around 16.6%.

Cotton/cellulose acetate biodegradable nonwovens

The first studied biodegradable cotton-based nonwoven fabrics were produced by cotton and ordinary cellulose acetate (OCA) fiber. Bonding temperatures used here for thermal calendering are 150°C, 170°C, and 190°C based on the ordinary cellulose acetate's high softening temperature (T_s: 180–205°C). The tensile strengths along machine direction of the bonded fabrics are listed in Table 10.4. However, the tensile strength of the nonwoven fabric made with cotton/cellulose acetate nonwoven blend is quite low and is not suitable for consumer application when it is processed under the temperatures associated with cellulose acetate's softening temperature (180°C–205°C). Solvent treatment has been introduced in order to modify the softening temperature of cellulose acetate fiber and to lower the calendering temperature, while maintaining enhanced tensile properties. Acetone, a good solvent for cellulose fiber, was considered a choice in the solvent pre-treatment. Twenty percent

Table 10.4 Peak load for cotton/cellulose nonwovens (kg)

	Bonding temperature (°C)	Binder component 25%	Binder component 50%
Cotton/OCA (No treatment)	150	0.10	0.03
	170	0.09	0.03
	190	0.09	0.09
Cotton/OCA (With 20% acetone solvent treatment)	150	0.21	0.20
	170	0.34	0.47
	190	0.69	0.65
Cotton/OCA (With water dip-nip treatment)	150	0.21	0.25
	170	0.37	0.44
	190	0.81	0.77
Cotton/PCA (No treatment)	150	0.17	0.25
	170	0.33	0.42
	190	0.63	0.90
Cotton/PCA (With water dip-nip treatment)	150	0.52	0.57
	170	0.80	0.86
	190	0.81	0.87

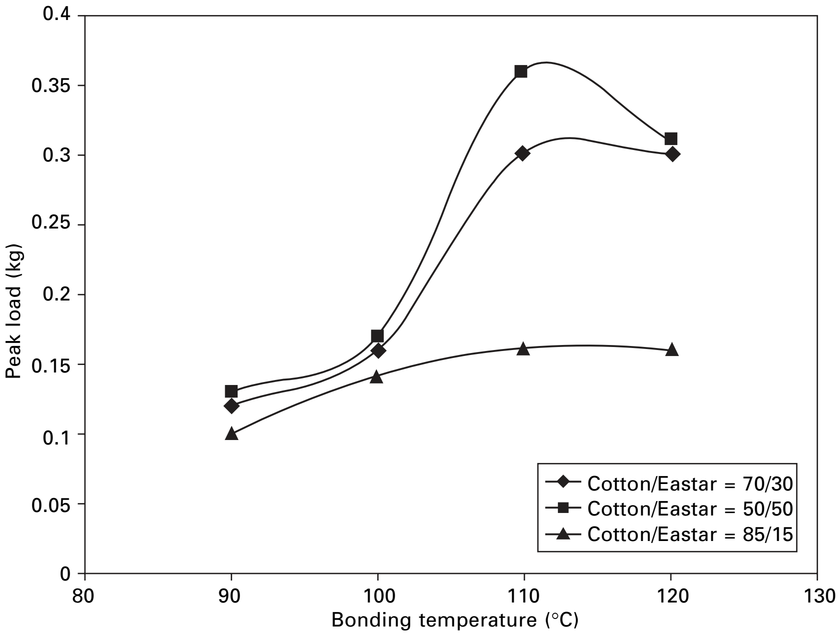
acetone solvent pre-treatment was then applied for cotton/cellulose acetate nonwovens to decrease the softening temperature and further lower the calendering temperature [24]. The results showed that these solvent treatments can decrease the softening temperature of cellulose acetate fiber and produce comparatively high tensile strengths as shown in the data in Table 10.4. However, from a practical standpoint, manufacturers do not like to have a process involving the use of acetone since acetone evaporates easily, and is flammable and toxic. These detrimental factors may cause big problems in manufacturing and pollute the working environment. Also, consumers may not prefer to buy acetone treated products.

Thus, two alternative methods were further applied for cotton/cellulose acetate nonwovens [25]. Water dip-nip treatment was further used instead of acetone solvent pre-treatment to make the process more environment friendly. Comparing the effect of water dip-nip treatment with acetone solvent treatment, it can be found that there is no significant difference between water dip-nip treatment and 20% acetone solvent treatment and peak load of cotton/cellulose acetate thermally bonded webs are enhanced by both the treatments. Based on these data, water can be used as an external plasticizer instead of 20% acetone solvent without compromising web strength and the process is environment friendly.

From the point of energy concern, it is better to make the whole process as simple as possible. So a plasticized cellulose acetate fiber, wherein an internal plasticizer was added during fiber manufacture to lower the softening temperature of ordinary cellulose acetate and further lower the bonding temperature during thermal calendering process. It can be clearly seen from the data (Table 10.4) that peak load has been improved by using PCA instead of OCA, especially at higher bonding temperature. Further comparison of external plasticizer (water) and internal plasticizer shows that there is no significant difference between using external plasticizer and internal plasticizer. Thus, it is evident that an internal plasticizer (PCA) can be used in place of the external plasticizer (water) without compromising web strength, and the process is more economical. Based on the above analysis, it seems that the optimal processing conditions are either for cotton/OCA with water dip-nip treatment or cotton/PCA without treatment bonded at 190°C for both the blend ratios. The optimal strength of the biodegradable nonwovens is around 0.8 kg.

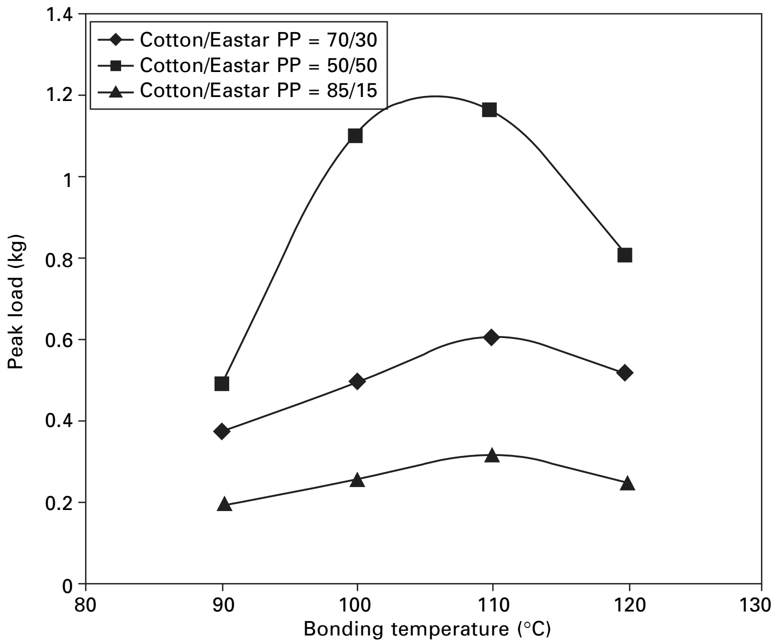
Cotton/Eastar biodegradable nonwovens

The desired calendering temperature of PCA bonded nonwovens is still much higher for achieving good tensile properties. So, a newly introduced biodegradable copolyester unicomponent (Eastar) fiber, which has a relatively low softening temperature (~80°C), was further selected as a binder fiber instead of cellulose acetate fiber. It has been reported that this binder fiber can be totally degraded into CO_2, H_2O and biomass [30]. Because of the low softening temperature of the binder fiber (T_s: ~80°C), bonding temperatures used are 90°C, 100°C, 110°C, and 120°C. The tensile strengths along machine direction of the cotton/Eastar fabrics are shown in Fig. 10.13. It can be seen that these strength values are higher than those of cotton/OCA nonwovens but much lower than those of cotton/PCA nonwovens as listed in Table 10.4.



10.13 Peak strength of cotton/Eastar nonwovens.

Unicomponent Eastar Bio® GP copolyester fibers are soft and somewhat difficult to crimp due to the high elasticity of the fiber. For carding process, relatively stiffer fibers are preferred. One disadvantage in using Eastar as a binder fiber is that it is hard to get the binder fibers well distributed, which may cause the low tensile properties of the final calendered nonwoven fabrics. Thus, a bicomponent fiber with Eastar Bio® GP copolyester as a sheath on a stiffer PP core was produced by Eastman Chemical Company, Kingsport, TN to offer more stiffness than a 100% unicomponent Eastar Bio® GP copolyester fibers and to further improve the tensile properties of the nonwoven fabrics. This bicomponent binder fiber has higher tenacity, higher crimps, and lower peak extension compared to that of Eastar unicomponent binder fiber as listed in Table 10.3. These properties are preferred for the carding process. The tensile strengths of cotton/(Eastar/PP) nonwovens are shown in Fig. 10.14. It can be clearly seen that the tensile strengths of the fabrics are much higher than those of cotton/Eastar nonwovens shown in Fig. 10.4, and even higher than cotton/PCA nonwovens. The optimal cotton/(Eastar/PP) web has a peak load value of 1.21 kg or 1.15 kg for the binder fiber component of 50% at bonding temperature of 110°C or 100°C respectively. Therefore, using Eastar/PP bicomponent fiber as a binder fiber can improve the tensile properties of cotton/Eastar nonwoven fabrics. The optimal thermal calendering temperature is relatively lower than that for cotton/cellulose nonwovens, which means that the cost of the process can be greatly reduced by using Eastar/PP bicomponent fiber as the binder fiber for the cotton-based biodegradable nonwovens.



10.14 Peak strength of cotton/(Eastar/PP) nonwovens.

Flexural rigidity and absorption properties of the cotton/(Eastar/PP) nonwovens were also studied. Results show that the nonwovens have good flexural rigidity and absorbency, which indicate that the nonwoven materials may be used for medical and sanitary applications. However, one has to remember that PP component in the bicomponent fiber is not biodegradable; this puts this fabric in the category of many other cotton/binder nonwovens that may have PP or PET as binder fibers. The results obtained from these studies suggest different routes for producing high strength nonwoven webs from cotton fibers with a thermoplastic binder fiber. Newer thermoplastic polymers are good candidates for such applications. In fact, recent work in our laboratory has shown that PLA can be used as a binder fiber to produce strong point bonded nonwoven webs. Another advantage is that PLA requires a relatively lower bonding temperature.

10.7.6 Wet laid disposable nonwovens with flax fiber

The use of bleached elementary flax fiber in modern disposable nonwoven products was recently studied by Van Roekel *et al.* [8]. Due to the long elementary fiber length and high cellulose content of flax bast fibers, they become an excellent substitution for synthetic fibers in disposable nonwovens. Wet laid nonwoven sheets were produced and spunlaced on a pilot unit, however, further improvement are reported to be needed for the process. Usually, wet laid disposable nonwovens are manufactured on fourdrinier-type paper machines, stock preparation and headbox are modified for long fibers, and surfactants are applied to help disperse the long fibers in the primary water cycle. The machine for wet laying flax nonwovens needs to be fast rewetting, easy dispersion in the existing stock preparation system and homogeneous formation. Various blends of 18 mm cut flax and PET fiber, supplemented with fluff pulp fillers were produced; no finishing was applied for the flax fiber for the process. A 1.5 m wide, 80 g m^{-2} web at about 100 m min^{-1} was formed. The properties of the resultant wet laid nonwovens are listed in Table 10.5. It was observed that the strength properties of the web disappear completely with the increase of flax content. When extrapolated to 40% flax content, strength can be fully attributed to the fluff pulp, and the strength of the web was not improved by adding more flax. Since the individual flax fiber has sufficient strength, the absence of tensile strength in the web was believed to be from the poor formation and bonding properties of the web. Therefore, further improvement of the wet laid process is needed either by using shorter flax fiber or applying finish to flax fiber to improve its dispersion.

Table 10.5 Wet laid nonwoven properties [8]

Property	Unit	Run 1	Run 2	Run 3
Flax	% w/w	10	20	30
Synthetic fiber	% w/w	20	20	10
Fluff pulp	% w/w	60	60	60
Weight	g m^{-2}	98.8	79.2	62.2
Density	kg m^{-3}	204	213	204
Tensile dry	Nm g^{-1}	15	14	9
Tensile wet	Nm g^{-1}	5.3	3.0	1.5
Elongation	% M/C	40	32	24

10.7.7 Nonwovens from animal fibers

Wool

Wool has been one of the most widely used animal fibers. The first nonwovens were produced from wool fibers as felts by mechanically interlocking the woolen fibers, taking advantage of their natural surface scales. Wool has excellent thermal properties and is one of the best insulating fibers. Because it is more expensive than many of the synthetic fibers used in nonwovens, it has not been one of the popular fibers. Lately, there is increasing effort to incorporate wool fibers in special nonwoven applications. Using nonwoven processes, it is possible to produce low-cost lightweight woolen fabrics with high stretch. Recent work [31] has shown that nonwoven fabrics from wool can be produced with properties that are not possible to achieve by knitting and weaving. Some of the apparel products that are produced from merino wool include three-dimensional coating fabrics, stretch fabrics, windproof fabrics, and footwear accessory fabrics.

Thermal blankets produced from wool fibers have excellent insulation and comfort properties. Also, these are waterproof and pack into a small volume, making them suitable for lightweight blankets for search and rescue operations. The combination of properties such as wicking ability, moisture and sound absorption, resiliency, and thermal insulation makes wool and wool-blend nonwovens suitable for many automotive uses. Thus, there is increasing effort to take advantage of wool's properties in many emerging applications. One such example is blending 20–35% wool with rayon to produce affordable WoolFelt® nonwovens by Natural Nonwovens [32]. These fabrics can be colored or textured as desired, and are considered as fabrics of choice for heritage quilts, penny rugs and heirloom crafts.

Silk

Silk, considered the queen of fibers, is an expensive fiber with many rich properties and being a natural protein fiber, it is known to be biodegradable. Because of the cost, this is not a fiber targeted for nonwovens. However, there have been efforts to produce silk nonwovens for niche applications; one advantage is that waste and poor quality silk can be used to produce many of the nonwoven products, thereby helping control the cost. Recently, spunlaced silk nonwovens with very low basis weight of 25 g m^{-2} have been developed using the Jetlace 2000 water jet machine form Rieter Perfojet [33]. These lightweight nonwovens are targeted for sanitary materials and medical applications such as gauze and wound dressings, cosmetics and skin care products, where the property demand might be stringent. Also, by using the hydroentangling process, using any other chemical additive is avoided. These fabrics have softness, elasticity, moisture absorption, heat preservation, breathability and are not harmful to the body in any way. Some of these nonwovens can also be used as high value garments as liner for overcoats, jackets, suits or fashion fabrics. There is likely to be continuing research and development in this area as the market realizes the potential for such fabrics and with the simultaneous efforts of reducing the cost by using waste silk.

Chitin

Chitin is a safe natural substance found in the shells of crabs, shrimp and lobster, and in the wings of butterflies, ladybugs etc. Chitin is one of the three most abundant polysaccharides in nature, in addition to glucose and starch. It ranks second to cellulose as the most abundant organic compound on earth. Chitin and its derivatives, chitosan, chitin oligosaccharide, and chitosan oligosaccharide, have many useful properties that make them suitable for a wide variety of health-related applications. Also, chitin products are known to be anti-bacterial, anti-fungal, anti-viral, non-toxic and non-allergic.

Nonwoven webs can be formed from chitin fibers for use in medical applications. The chitin artificial skin is a newly developed patented product produced by a process technology [34]. The chitin fiber is produced by special wet laid spinning process with the selected chitin; it has the properties of three-dimensional structure, soft handle, absorbency, breathability, non-chemical additive, compact texture, softness and smoothness, thus it is the ideal dressing for extensive burn, scald and other traumas. Main features are: inhibition of bacterial growth avoiding cross-infection and control of the loss of the exudates, good biocompatibility, excellent bioactivity, stimulation of new skin cell growth, accelerated wound healing, no adverse reaction of abnormal immunity, repelling and irritation. As well as artificial skin, other products include wound protective bandages, wound dressings, and skin beauty packs.

Chicken feather

Feather products have been used in bedding and some outerwear for cold climates. Nonwoven battings made from chicken feather fibers have been evaluated as possible insulating materials. When compared with goose and synthetic fibers, chicken feather batts show insulating properties better than that of synthetic fibers and close to that of downs. Also, the chicken feather battings have good resiliency, which is important for insulation battings. One disadvantage is that the properties of chicken feather, both size and tenacity, vary depending on how they are separated from the quill [35]. This introduces further non-uniformity and the process has to be very well controlled to compensate for this.

10.7.8 Spunbond biodegradable nonwovens

Spunbond PTAT nonwovens

The Eastar Bio® GP copolyester (PTAT) can be melt spun into spunbond and melt blown fabrics. It has been reported that uniform spunbond fabrics have been produced on Ason spunbond equipment using slotted air technology and Reifenhauser Reicofil equipment at conventional spinning speeds [36]. Fabrics with finer fibers, higher throughputs, higher spinning speeds (> 4500 m min^{-1}), and basis weight ranges from 14 to 130 g m^{-2} have been successfully obtained. The resultant spunbonded fabrics are semi-crystalline with good drapeability, soft hand, and elastic properties. The fabrics can be gamma radiation sterilized; radio frequency bonded, and ultrasonically sealed, which make the fabrics suitable for medical applications, such as hospital surgical packs, wipes, bondages, face masks, etc. The fabrics can also be used for agricultural and other absorbent disposable products like diapers, seed mats, ground cover, etc.

Spunbond PLA nonwovens

Polylactic acid (PLA) first received considerable attention because of its biodegradability and biocompatibility; in recent years, researchers are paying more attention on biodegradable nonwoven products. Polylactic acid (PLA) was spunbonded and melt blown at the University of Tennessee, Knoxville in 1993 [37]. Later, Kanebo, a Japanese company, introduced Lactron® (poly-L-lactide) fiber and spunlaid nonwovens in 1994. Biesheim-based Fibreweb (France) has developed nonwoven webs and laminates made of 100% PLA in 1997 and introduced a range of melt blown and spunlaid PLA fabrics under the brand name of Deposa™ [38]. The composite structures, described in US Patent 5,702,826 [39], comprise one or more plies of nonwoven laminated to a film, where all the plies were totally manufactured from polymers derived form lactic acid. Each ply provides mechanical, barrier-effect, absorption, filtration and thermal insulation properties that can be adapted to each application by selecting the suitable composition of the nonwovens and of the films based on polylactic acid. The spunbonded nonwoven layer is used as the support, the film provides impermeability and barrier effect, and another spunbond or melt blown nonwoven layer is added to offer filtration/absorption and thermal insulation properties. Depending on the application, a derivative of lactic acid chosen from D-lactic acid, L-lactic acid, or DL-lactic acid may be used.

The PLA polymers are processed using conventional spunbond or melt blown techniques. The plies of the nonwovens can either be hot calendered, needle punched, hydroentangled, or chemical bonded. They are intended for disposable hygiene, agriculture, and medical applications such as diapers, sanitary napkins, protective clothing, surgical masks and drapes. An example of the three-ply nonwoven for medical application consists of the first spunbond web with a basis weight of 10–20 g m^{-2} and the linear density of the fibers between 1.5–2.5 dtex, the melt blown web with basis weight of 5–15 g m^{-2} and the linear density of the fibers between 0.1–0.3 dtex, and the second spunbond with a basis weight of 10–20 g m^{-2} and the linear density of the fibers between 1.5–3.0 dtex. The total weight is from 25–55 g m^{-2}. The calendering temperature for the laminate is between 65–120°C depending on the type of raw material and the calendering speed. The laminate has a bonded surface area of 8–15%. The strength of the composite is between 40–100 N and the elongation at break is from 30–60%.

10.7.9 Melt blown biodegradable nonwovens and laminates

In JP Patent 11,117,164 [40] a kind of biodegradable nonwoven laminate of melt blown nonwoven fabrics of aliphatic polyester fibers and spunbonded nonwoven fabrics of urethane bond-containing butylene succinate copolymer fibers was described. The biodegradable laminates were prepared by sandwiching melt blown nonwoven fabrics of biodegradable aliphatic polyester fibers with diameter of 0.5–2.0 μm between spunbonded nonwoven fabrics of long fibers consisting of polymers containing 1,4-butanediol units and succinic acid units and having urethane bonds to give laminates with melt blown nonwoven fabric content of 10–30%. The fabrics are useful for medical care materials and hygienic materials. Bionolle 1030 (butylene succinate copolymer containing urethane bonds) was melt spun at 190°C, passed through an ejecter, and piled on a screen to give spunbonded nonwoven fabric. Bionolle 3300 (butylene succinate copolymer containing 20 mol% adipic acid units and urethane bonds) was melt spun by a melt blowing method, sandwiched between two spunbonded nonwoven layers of Bionolle 3300 fibers, and embossed at 105°C to give a laminated nonwoven fabric with tensile strength 151 N and softness rating 98 and exhibiting weight loss more than 50% on embedding the nonwoven fabric in soil for 6 months.

10.7.10 Wet laid nonwoven fabrics with PLA fiber

In JP Patent 2003,268,691 [41], wet laid nonwoven fabrics comprising biodegradable fibers consisting of biodegradable polymers derived from sources other than wood and petroleum were described. The wet laid nonwoven fabrics comprise more than 90% biodegradable fibers consisting of PLA, or the wet laid nonwoven fabrics comprise more than one portion of the biodegradable fibers comprising fibrillated fibers. The wet laid nonwoven fabrics are reported to be useful for packaging paper, corrugated cardboard, tissue paper, printing paper, wiping paper, toilet paper, and filter paper and for agriculture. Thus, 5:95 D-lactic acid:L-lactic acid copolymer chips were melt spun at 260°C and wound to give undrawn fibers. The wound fibers were drawn at hot roll temperature of 80°C and heat-setting temperature of 118°C to give drawn fibers with elongation 40% and denier per filament 2.2 dtex. The undrawn fibers and drawn fibers were crimped and cut to give undrawn staple fibers with 5.24 crimps cm^{-1} and drawn staple fibers with 5.20 crimps cm^{-1}. The drawn staple fibers were passed through an orifice at high speed and impacted against a wall at the exit of the orifice to give fibrillated fibers. A dispersion contains 60:15:25 mixture of undrawn staple fibers:drawn staple fibers:fibrillated ultrafine staple fibers were made into a wet laid nonwoven fabric using a mesh drum, dried at dryer surface temperature of 110°C, and calendered at 140°C to give a biodegradable nonwoven fabric showing complete fiber degradation on embedding the nonwoven fabric in a compost for 50 days.

10.8 Applications of biodegradable nonwovens

Biodegradable nonwovens can be used for almost all the areas of nonwoven applications. In sanitary and medical industries, a hair cap made of a poly(L-lactic acid)-based thermoplastic resin nonwoven fabric showed good hair-capturing property according to JP Patent 2002345541 [42]; breathable, biodegradable/compostable disposable personal care product was produced from Bionolle 3001 nonwovens reported from WO Patent 2002053376 and JP Patent 2002035037 [43, 44]. Natural coconut fibers (coir) have been applied for biodegradable erosion control mats by Landlok [45] in the geotextile industry. In the automotive industry, most of the European automotive producers already use car interiors made of natural fibers. In Germany, in 1996, 3630 tonnes of flax, sisal and jute were used for car interiors, and in 1999 this figure increased to 11,800 tonnes. The absolute figure of the production at the moment is not very high, but the average annual growth, which is round about 50%, is promising [46]. Nonwovens made from kenaf fiber [47] offer good sound insulation property for automobile interiors. Yachmenev *et al.* [48] reported that a variety of moldable, cellulosic-based nonwoven composites for automotive applications with excellent thermal insulation properties were fabricated from kenaf, jute, flax, and waste cotton using recycled polyester and substandard polypropylene. In filtration industry, refuse bag and drain filter have been made by using fine denier biodegradable polylactic acid nonwovens for the application of sink drain [49]; biodegradable pleated filter material and filter unit for air purification and liquid filtration are produced [50].

10.9 Flushable nonwovens

Liquid waste system disposal is quite attractive compared to solid waste disposal, where infrastructure is not well developed for the latter. Also, in many instances, landfill and solid waste disposal techniques have some other environmental related problems. Considering this, the wastewater system is more convenient, hygienic and environmentally sound; already there is a massive infrastructure in place as wastes from houses go to industrial biodegraders in the form of sewage farms, or local biodegraders or septic tanks. In such situations, many disposable products can be flushed in the system rather than thrown away as solid waste [51].

Flushable nonwoven diapers, liners and wipes have been in the market for a while. For such products, flushability is desirable and technically it is possible to develop such products. However, lack of convenience and cost issues have driven the market towards non-degradable plastics in diapers as well as feminine hygiene products. In designing and developing flushable nonwovens, one of the challenging requirements is that the products have to be strong enough to be stored and/or used when wet, but at the same time, should be weak enough to break down in the sewage system.

Flushability itself is not well defined and there is no accepted standard method to evaluate and certify flushability of such products. The current efforts involve comparing fabrics by agitating them in a standard volume of water for a standard time and observe the fragmentation degree or determine the time for achieving full dispersion. For a nonwoven material to be claimed flushable, the fabric must break up immediately in a toilet bowl and be small enough to be transported from the toilet bowl to the sewage system in a single flush. It should not lead to blocking of pipe work and there should not be any accumulation in subsequent flushes. There have been consumer studies that have shown that many flushable wipes in the market lead to clogging of pipes.

In addition to the fact that they have to break down, they should not contain any chemicals that might affect the functioning of sewage farms or the quality of the treated water. This means that all the materials used have to be biodegradable. With these stringent requirements, some of the means of achieving these are:

- Hydrogen bonded cellulose without other bonding as in toilet tissue paper. These will consist of cellulosic fibers, refined pulp and fibrillated fibers that give stronger products that can be dispersed in water. However, these are likely to be stiffer in nature.
- Hydrogen and friction bonded cellulose wherein carded, air laid or wet laid fiber web is hydroentangled. By controlling the process conditions, it should be possible to develop a structure that is dispersible in water under the suggested conditions.

- Fibers bonded with water-soluble polymers such as starches, carboxymethyl cellulose, polyethylene oxides, polyvinyl alcohols, polyacrylates, etc. This may involve bonding of biodegradable fibers or films or other structures that will break down in the flush.

In many of these situations, the enhancement of wet strength will retard flushability. There has been more focus on development of systems where wet strength is enhanced for storage and use, but not in the sewage system. In most of the systems, there seems to be a compromise where the performance has to be sacrificed to achieve flushability. Some of the approaches have been to employ water-sensitive binders with salts, which enhance the solubility of the binder in the solution. For wet wipes, other alternatives suggested are to use a system where the wipes remain dry till they are ready to use, wherein a wet additive is incorporated just as it is being dispensed. Another suggestion is, possibly, to modify the toilets and flushing systems to handle new materials, where the breakdown is accelerated either by additional chemical or mechanical action [51].

When one looks at all the available materials and processing technologies, air laid and wet laid systems are more suitable. The problem with spunbond types is the difficulty of breaking down continuous fibers; using short fibers to form webs and binding them with fibers that are biodegradable or water soluble will be the best approach. There is a lot of patent activity indicating interest and inclination in the industry to develop such products. One such example is the introduction of a new biodegradable polymer Nodax® (a polyhydroxyalkanoate), which may be used for flushable nonwoven products, and other biodegradable nonwoven materials as well.

10.10 Leading producers of nonwovens

There are many companies both big and small involved in various aspects of nonwovens, from producing polymers, fibers, additives, making machinery, producing nonwoven roll goods and converting the nonwovens into final products. Table 10.6 shows companies that are leading producers of nonwovens, and although there may be slight shift in the ranking of a few companies over the years, overall these companies continue to be major players [52].

10.11 Sources of further information and advice

As the nonwovens industry is continuing to grow, there is a lot of new information available with new materials and products coming into the market continuously. It is advised that the readers refer to some of the valuable resources for latest updates. Some of the important organizations and other resources are listed below with their url information.

Table 10.6 Leading producers of nonwovens [52]

Company	Worldwide sales in 2003 (millions USD)
Freudenberg	1,400
DuPont	1,200
Kimberly-Clark	925
BBA Group	900
PGI	730
Ahlstrom	728
Johns Manville	500
Colbond	250
Buckeye Technologies	217
Japan Vilene	185
Asahi Kasei	167
Hollingsworth & Vose	165
Lohman	158
Foss Manufacturing	157
British Vita	154

10.11.1 Important organizations

Association of the Nonwovens Fabrics Industry, Cary, NC, USA – INDA (www.inda.org)
European Disposables and Nonwovens Association – EDANA (www.edana.org)
Technical Association of the Pulp, Paper and Converting Industry – TAPPI (www.tappi.org)
China Nonwovens Technical Association – CNTA (www.cnta.org)
Technical Textiles and Nonwovens Association – TTNA (www.ttna.com.au)

10.11.2 Prominent university centers

Nonwovens Cooperative Research Center, North Carolina State University, Raleigh, NC – NCRC (www.tx.ncsu.edu/ncrc)
Textiles and Nonwovens Development Center, University of Tennessee, Knoxville – TANDEC (web.utk.edu/~tandec)
Nonwovens Research Group, Department of Textiles, Leeds, UK – NRG (www.nonwovens.leeds.ac.uk)

10.11.3 Books and other publications

Nonwovens Handbook, edited by Russell, S. Woodhead Publishers, 2005.
Nonwoven Textiles, by Jirsak, O. and Wadsworth, L.C. Carolina Academic Press, Durham NC, 1999.
Nonwoven Fabrics – Raw Materials, Manufacture, Applications,

Characteristics, Testing Processes, by Albrecht, W., Fuchs, H. and Kittelmann, W. Wiley-VCH, Weinheim, 2003.
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TANDEC Conference Proceedings.
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Nonwovens information and business network – www.nonwovens.com
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