Understanding the Effect of Machine Technology and Cellulosic Fibers on Tissue Properties – A Review

Tiago de Assis,[a] Lee W. Reisinger,[b] Lokendra Pal,[a] Joel Pawlak,[a] Hasan Jameel,[a] and Ronalds W. Gonzalez [a,]*

Hygiene tissue paper properties are a function of fiber type, chemical additives, and machine technology. This review presents a comprehensive and systematic discussion about the effects of the type of fiber and machine technology on tissue properties. Advanced technologies, such as through-air drying, produce tissue with high bulk, softness, and absorbency. Conventional technologies, where wet pressing is used to partially dewater the paper web, produces tissue with higher density, lower absorbency, and softness. Different fiber types coming from various pulping and recycling processes are used for tissue manufacturing. Softwoods are mainly used as a source of reinforcement, while hardwoods provide softness and a velvet type surface feel. Non-wood biomass may have properties similar to hardwoods and/or softwoods, depending on the species. Mechanical pulps having stiffer fibers result in bulkier papers. Chemical pulps have flexible fibers resulting in better bonding ability and softness. Virgin fibers are more flexible and produce stronger and softer tissue. Recycled fibers are stiffer with lower bonding ability, yielding products that are weaker and less soft. Mild mechanical refining is used to improve limitations found in recycled fibers and to develop properties in virgin fibers. At the same time that refining increases strength, it also decreases bulk and water absorbency.

Keywords: Tissue paper properties; Softness; Water absorbency; Wet strength; Dry strength; Tissue machine technology; Cellulosic fibers; Mechanical refining

*Contact Information: a: Department of Forest Biomaterials Science and Engineering, Box 8005, North Carolina State University, Raleigh, NC 27695-8005, USA; b: ReiTech Incorporated, 26 The Point, Coronado, CA, 92118, USA; *Corresponding Author: rwgonzal@ncsu.edu*

INTRODUCTION

Hygiene tissue paper products are manufactured to meet the desired performance according to a specific application inside a market segment. Overall, water absorbency, softness, strength (dry or wet), and disintegration are the most important properties used to evaluate the performance of tissue products. The observed properties of commercial tissue products are basically a function of fibers, chemistry, and manufacturing technology. There is a vast number of fiber types, tissue machine technologies, and chemical additives available in market for manufacturing of tissue products. Inside this complex environment, tissue paper manufacturers have to choose the right combination of fibers, additives, and technologies to produce specific tissue products capable of achieving the desired performance while providing enough profitability to the producer. Motivated by the complexity of this task, the main objective of this review is to present a discussion about how tissue paper properties can be tuned as a function of fiber type and tissue machine technology. This review brings a comprehensive description about a) tissue products, grades, and their properties, b) a comparison of product performance from different tissue machine technologies, c) properties of different type of fibers, and d) the effect of mechanical refining on tissue properties. Even though chemical additives (*e.g.* softeners, surfactants, strength additives) are commonly used in tissue manufacturing to improve tissue properties, this article will not cover this topic. Information about the use of chemical additives in tissue manufacturing can be found elsewhere (Neal 1990; Forbess 1997).

Tissue Paper Definitions, Products, Market and Grades

Based on their function, paper products can be placed in three main categories: i) packaging - defined as packaging materials, ii) printing and writing - defined as graphic papers, and iii) wiping and absorbing - defined as household and sanitary papers. Products in the third category, also known as tissue and hygienic papers, have a wide range of types and applications, including facial tissue, toilet tissue, napkin, kitchen towel, hand towel, and wipes. Some tissue papers are also used in the manufacturing of baby napkins and sanitary towels (Hubbe 2006; Kilby and Crevecoeur 2014; FAO 2017a). Nowadays, tissue paper, together with packaging products, are the most promising sectors in the paper industry due to the constant increase in demand. The global production of tissue paper has been in constant growth for the past ten years (average annual growth rate is 2.6%), reaching a global production of 32.8 M tonnes with a total market value of $ 72.8 billion in 2015 (Euromonitor 2017; FAO 2017b).

This diverse assortment of tissue products is commercialized in two market segments: i) Away From Home (AFH), professional or institutional segment; ii) At Home (AH), domestic or consumer tissue segment (Tprint 2011). AFH products are designed and sold for non-domestic consumption. Consumers typically use those products in workplaces, catering services, and public places (*e.g.* offices, industries, restaurants, arenas, hotels, malls, parks) (Wrap 2005). The customers of AFH products are institutions that buy tissue products from manufacturers or resellers and decide what products they want to buy to satisfy their customer's (consumer) needs. Therefore, the consumption of those products, from the final consumer perspective, comes as a secondary need. In other words, if consumers want to go out to have a nice dinner, it is more likely that they would prefer to go to a restaurant that offers their favorite food than going to a place with premium napkins. On the other hand, AH products are designed for domestic consumption and are usually found at wholesalers or retailers. The consumption of those products come as the primary need for consumers. In this case, consumers will decide about what tissue product to buy based on the desired performance and price. For example, if consumers prefer to use very soft, white, and strong bath tissue, it is more likely that they would prefer to buy a premium product than a basic bath tissue, even though they would have to spend more money to satisfy their needs.

Tissue products are manufactured and sold in a variety of brands that can be divided into two major groups: a) National Brands (NB) and b) Private Label Brands (PLB). NB are brands owned by the manufacturers and PLB are brands owned by wholesalers or retailers. After its appearance more than a century ago, PLB became very popular among retailers and consumers (Hyman *et al.* 2010). In 2015, the PLB market share in the tissue market was approximately 27% in the USA (with a growth of 9% over the last ten years in the USA) and 67% in Western Europe (Pöyry 2015). With the commercialization of PLB products, retailers have the potential to increase their overall profits. PLB products are typically purchased by retailers at prices slightly above the marginal costs (8% to 10% margin), and usually retailers spend much less on research and development, product launching, selling and advertising. As a result, by commercializing PLB products, retailers would have higher gross margin and higher bargaining power when compared to NB products. Additionally, PLB products contribute to building retailer's chain image and boosting customers' loyalty, especially when PLB products have constant and good quality. Manufacturers can also benefit with the production of PLB products. PLB production has the potential to reduce manufacturer's unit fixed costs *via* economy of scale when NB and PLB are produced together. Additionally, PLB production will reduce the participation of competitors in the market place and will increase cooperation with retailers. However, PLB production can result in losses to manufacturers due to insufficient profit and cannibalization of their own NB products. Usually, non-leading NB manufacturers benefit the most with PLB production. Typically, PLB consumers are price-sensitive and value-oriented, willing to pay less in a given product category. On the other hand, consumers that are more influenced by advertising and are less price-sensitive, relying on unquantifiable experience attributes, tend to choose NB products (Hyman *et al.* 2010).

Table 1. Matrix of Fiber Types and Technology Used to Make a Range of AFH Tissue Products and Grades in the European Market (adapted from Wrap 2005)

Tissue Grade		Economy → Premium				
Machine Format		Wet Crepe	Dry Crepe			TAD
Recycled Fiber Content	Likely Recycled Content	100%	50%-100%	50%-100%	40%-80%	< 20%
	Possible Recycled Content	100%	100%	100%	100%	50%-70%
Paper Application	Toilet Tissue (rolls and packs)		🟥 usually, 100% recycled	🟧 >60% recycled	🟨 20% - 100% recycled	
	Hand Towels (folded and rolled)	🟧	🟥 usually, 100% recycled	🟥 Usually, 100% recycled	🟧 usually > 80% recycled	🟨 Very limited available
	Facial Tissue		🟧 40% - 100% recycled	🟥 <60% recycled	🟧 Max 60% recycled, often 0%	🟨
	Napkins and Serviettes		🟧 80% - 100% as found in fast food retail	🟥 80% - 100% as found in fast food retail	🟧 0% - 80%	🟨

🟥	Most common paper type used for this application/product
🟧	Some products will fall into this grade
🟨	Rarely used

As a function of fiber properties, chemistry, process conditions, and technology, tissue products can be classified in three major grades or categories: a) Economy and Value products (EV); b) Premium products (PR), and c) Ultra products (UL). EV products are the most affordable products, capable of meeting minimum performance requirements. Those products have one or two plies and are manufactured with conventional technology, such as wet-creped and dry-creped technologies. EV products have high content of recycled and low quality fibers (such as mixed office waste, old corrugated containerboard). PR products can also be manufactured with conventional technology. However, they usually have a lower content of recycled fibers when compared to EV products. UL category accounts for more expensive and high-performance products, manufactured with a minimum amount of recycled fibers. UL products are usually manufactured combining advanced technologies, such as through-air drying (TAD), high content of virgin and high-quality fibers, multiple plies (2 or 3), and chemicals (softeners, debonders, wetting agents) (Fisher 2016; Zou 2017).

Table 1 presents a matrix that illustrates the type of fiber and technology used to manufacture AFH products in the European market. The likely content of recycled fibers in AFH products may range from up to 100% to as low as 20% as product category moves from EV products (manufactured with conventional technology) to UL products (manufactured using advanced technology). As a result of type of fiber and technology, the final properties of tissue products improve as one goes from the left to the right side of the matrix. For example, the combination of proper virgin fibers and advanced technology would result in a high bulk and soft tissue product with good absorbency. On the other hand, the use of the high content of recycled fibers and conventional technology would result in a denser tissue paper with lower softness and lower absorbency (Wrap 2005).

TISSUE PAPER PROPERTIES

Tissue properties are much more influenced by consumer desires than by manufacturing needs (Novotny 1988). Every tissue product is designed for a specific application and performance, which will determine their primary, essential or functional properties. For example, kitchen towels are mainly used for cleaning and absorption purposes (Council of Europe 2004). When consumers use a kitchen towel, they usually expect to have a strong product, especially under wet conditions, capable of cleaning a dirty wet surface without breaking apart. Another important property for kitchen towels is absorbency. Consumers expect that kitchen towels would be capable of absorbing and holding as much water as possible when they have to dry a wet surface. Therefore, wet strength and absorbency could be considered as the primary, essential or functional properties of kitchen towel products (Kim *et al*. 1994; Loebker and Sheehan 2011; Kan and Wong 2015). Other properties, such as softness, brightness, and appearance could be considered as secondary properties because those usually do not have a significant contribution to the main purpose of kitchen towels (cleaning and drying surfaces). However, it is important to highlight that the distinction between primary and secondary properties is based on the functionality of the products and it is not based on particular needs of a different group of consumers in different market segments and geographic regions. For example, softness has become an important property for the marketing of kitchen towels. Even though a soft towel will not help to dry a wet surface better, consumers that are sensitive to softness would still seek for such products to satisfy their needs of experiencing a better hand feel comfort (Kim *et al*. 1994; Kan and Wong 2015).

According to Zou (2017a), target properties for tissue products in the American market change among different applications. Softness and strength are desirable for bath tissue, while absorbency is also important for facial tissue. For napkins, strength and absorbency are target properties, while bulk is also important for towels. According to Novotny (1988), softness, absorbency, and brightness are very important for bath and facial tissue, while absorbency and strength are more essential for towel and napkin. Table 2 presents the suggested primary properties of some AFH tissue products in the European market and Table 3 presents a benchmark comparison among all the national brands of kitchen towels in the USA market.

Table 2. Summary of Primary or Essential Properties of AFH Tissue Products in the European Market (Adapted from Wrap 2005)

Products and Properties	Strength	Wet Strength	Softness	Absorbency	Brightness and Color
Toilet Tissue			+		+
Facial Tissue			++		+
Hand Towels	+	+		++	
Napkins and Serviettes			+		++

Table 3. Summary of Machine Technology and Properties for All National Brands of Kitchen Towels in the USA Market (Adapted from Gonzalez *et al*. 2018)

Samples	Nº Plies	Machine Technology	Basis Weight (g/m^2) [1]	Bulk (cm3/g) [2]	Wet Tensile Energy Absorption (J/m^2) [3]	Water Absorbency Capacity (g/m^2) [4]	Softness (Tissue Softness Analyzer) [5]
A	2	CTAD [6]	51.4	6.5	9.8	828	17.4
B	1	DRC [7]	63.4	6.1	9.9	711	18.7
C	1	UCTAD [8]	55.6	6.5	10.7	622	19.5
D	2	CTAD	49.8	7.1	9.0	685	22.7
E	1	CTAD	40.6	6.6	8.0	567	22.3
F	1	UCTAD	38.7	6.1	6.6	466	25.6
G	2	LDC [9]	47.3	4.6	3.5	462	26.0

[1] Basis Weight (TAPPI T 410)
[2] Bulk (TAPPI T 411)
[3] Wet Tensile Energy Absorption (ISO 12625-4)
[4] Water Absorbency Capacity (ISO 12625-8)
[5] Softness (Tissue Softness Analyzer): real softness measured with Tissue Softness Analyzer - EMTEC. The lower the value, the softer is the sample.
[6] CTAD: Creped Through-Air Drying (Advanced technology)
[7] DRC: Double Re-Crepe (Advanced technology)
[8] UCTAD: Un-Creped Through-Air Drying (Advanced technology)
[9] LDC: Light Dry-Crepe (Conventional technology)

Bulk

Bulk is defined as the volume occupied by a given weight of paper. It is the inverse of apparent density and can be correlated with many other mechanical properties of paper (Thorp 1991). Bulk is an important property for tissue products because paper thickness and bulk correlates well with absorbency and bulk softness (Novotny 1988). Compaction of the fiber network is an unwanted effect if the target is to produce a very bulky product. A higher bulk can be achieved when tissue product is manufactured with advanced technologies (*e.g.*, TAD process), where wet pressing of the paper web is minimized. Other process conditions, such as the use of lower pressure in the press nips, milder refining of fibers, and paper creping will also contribute to higher bulk (Kullander 2012). Besides technology, fiber type also plays an important role in tissue bulk. Cellulosic pulps, such as eucalyptus and southern hardwood, produced from species having high Runkel ratio (2 x cell wall thickness / lumen diameter) are more rigid and less prone to collapse, resulting in a thicker and bulkier paper product. Additionally, high yield pulps can also be used to produce a higher bulk tissue product. High yield pulps are less flexible than low yield pulps due to their higher content of lignin and lower porosity, resulting in a more rigid structure (Nanko *et al.* 2005). Recycled bleached kraft fibers, with a history of drying, tend to be stiffer and less conformable, which will result in a higher bulk paper product that is desirable for tissue production. However, many recycled fibers already have been refined extensively, tending to produce a relatively dense sheet of paper (Hubbe 2006).

Absorbency

Absorbency is an important property for toweling and other tissue products with the purpose of wiping liquids. Absorbent tissue products should be capable of readily absorbing water (absorbency rate) and retaining a high level of absorptivity (absorbency capacity) until the end of the task (Kullander 2012). The ability to absorb liquid depends on having a high capillary pressure to suck the liquid and high permeability to allow the fluid to quickly flow away from the point of insult. The arrangement of hydrophilic fibers in a low density paper structure is responsible for the absorbent behavior of tissue products (Beuther *et al.* 2010). When paper products get in touch with water, the first phenomenon is surface wetting, followed by the penetration of water inside the paper structure. The penetration phenomenon is a very complex process because it will cause swelling of fibers as water is absorbed into fiber cell wall, resulting in changes in volume and pore structure of the paper (Thorp 1991). Absorbency properties are influenced by chemical properties of fiber surface and porosity of the paper web structure (Kullander 2012). Absorbent products have large amounts air-filled spaces among the fibers in the paper structure (Hubbe 2006). Absorbency can be controlled by fiber type, refining, creping, plies, and additives (Kullander 2012).

Fibers containing high content of lignin have lower water absorbency. For example, due to its high content of lignin, mechanical pulps can absorb about 1 gram of water per gram of pulp, while bleached fibers, such as kraft fibers, can typically absorb 5 to 10 grams of water per gram of fiber. Lignin removal increases hydrophilicity, porosity, and swellability of bleached kraft fibers, resulting in improved water uptake. The extractives present in cellulosic fibers also have a hydrophobic behavior. On the other hand, absorbency of cellulosic fibers is positively correlated with the content of hemicellulose (Hubbe *et al*. 2013). Tissue products manufactured with curly fibers are bulkier and more absorbent (Trepanier 2017). Bath tissue and towel products are made from lightly refined fibers to maintain initial relative stiff and tube-like nature of fibers that are necessary to achieve a high level of absorptivity (Thorp 1991; Hubbe 2006).

Typically, in a saturated tissue product, water is located in the spaces between plies, spaces between fibers, in the fiber lumen, and inside the cell wall. Within the cell wall, water can be located in micro, meso, and macropores. Water present in micropores is classified as non-freezing and freezing water. Non-freezing water corresponds to the first layers of water associated with the biomass surface. Freezing water corresponds to the water that has a depressed melting temperature due to the curved interfaces in micropores. The water present in macropores has similar thermodynamic properties to those of the bulk that is also present in the lumen, between fibers, and between plies (Kullander 2012). Most of the absorbed water is located in the spaces between fibers, and machine technology is an important variable to create inter-fiber spaces. TAD machines produce tissue products with higher bulk and higher absorbency than conventional machines. The number of plies also influences the absorbency, but to a lower degree when compared to the type of technology. The space between plies improves not only the absorbency capacity due to the creation of inter-ply water storage, but it also improves the absorbency rate. Lamellar flow channels are created between the plies, and such channels reduce the viscous flow resistance and improves absorbency rate. The absorbency capacity gained with the additional ply is usually greater than the capacity held within a single ply (Loebker and Sheehan 2011).

Strength

Tissue products are exposed to stresses and strains during the manufacturing of tissue jumbo rolls (*e.g.* paper machine, creping, winding), conversion of the jumbo rolls into the consumer size products (*e.g.* unwinding, embossing, perforation, rewinding, log sawing) (Brown 1991), and final use by the consumers (*e.g.* pulling, tearing, scrubbing, drying). Under those conditions, tissue has to be designed to develop strength properties necessary to meet stresses and strains requirements during manufacturing and while used by consumers.

Basically, the strength of paper is a function of three factors: i) strength and arrangement of fibers in the tissue web; ii) level of molecular bonding among fibers; iii) presence of strength additives. The first two factors are affected by processes variables and feedstock type. Chemical processes, such as bleaching, can reduce fiber strength, while refining and wet pressing usually improve bonding between fibers (Thorp 1991). Tissue products manufactured in tissue machines where pressing is used to partially dewater the tissue web (*e.g.* dry-creped) are stronger than tissue products produced in a TAD machine where minimal pressing is applied. However, the pressing increases the density of the tissue web, making it less absorbent and less soft (Liu 2004). In the same direction, refining increases the density of the tissue web which decreases absorbency and softness (Kullander *et al*. 2012). Long fibers promote higher strength because they have higher capability of forming bonds with multiple fibers. Fibers having high curl (curvature) will form tissue paper with lower tensile strength due to the reduction of number of inter-fiber bonds. However, more entanglement among fibers is observed when curly fiber are present in the tissue web, which contributes to higher wet strength and higher tear strength. For a given strength, increasing fiber length or decreasing fiber curl will result in higher bulk (Trepanier 2017). Higher hemicellulose content also improves bonding strength (Liu 2004). Because of better bonding ability, virgin and chemical pulps yield stronger tissue products than recycled and mechanical pulps, respectively (Novotny 1988).

Strength is dependent on the orientation of the tissue with respect to the applied stress (*e.g.* machine direction, cross direction, thickness direction). Machine and cross direction tensile strengths are usually higher than thickness direction tensile. Due to fiber orientation and creping process, tissue that is evaluated in the machine direction usually has higher strength and higher elongation than when evaluated in the cross direction. This behavior permits tissue products with high elongation capacity to respond better to converting shocks than a stronger tissue with low elongation (Thorp 1991). Tensile strength measurements performed in commercial kitchen towels shows that products presenting higher elongation capacity usually have better tensile strength (Kan *et al*. 2016).

Tensile failure of paper products happens due to a combination of inter-fiber bonding failure and fiber failure. For paper products where the inter-fiber bonding is well developed, such as printing and packaging products, it is expected that the failure of the paper will involve a substantial proportion of fiber failure. On the other hand, in paper products where the inter-fiber bonding is not so well developed, such as tissue products, the failure is more likely to happen as a result of bonding failure (Page 1969). Therefore, if someone develops a tissue product with very high bonding strength, the tensile failure is more likely to happen as a result of fiber failure. However, bonding strength typically is much less than fiber strength in the case of tissue paper. Therefore, the strength of tissue paper is mostly limited by the strength of the inter-fiber bonding. Many process variables influence the strength and elongation of tissue paper, including, pulping conditions, refining, fiber orientation, formation uniformity, wet pressing, drying tension, creping, and converting. Formation uniformity (sometimes called "uniform randomness") is an important factor. The basis weight of tissue paper is not the same at all points. As a result, the measured strength represents the strength of the weakest point in the sample. Products having poor formation will be weaker than products with same structural aspects but presenting better formation (Thorp 1991). In other words, the non-uniform formation can create weaker points in the paper web that will be more susceptible to failure. As a result, papermakers constantly look for process and chemical alternatives to enhance bonding strength (*e.g.* refining, strength additives) and uniformity of web formation (Hubbe 2006).

Paper tissue under stress will exhibit visco-elastic behavior. At low strain levels paper behaves elastically (reversibly), where the force increases linearly with strain. Most of the elasticity observed in tissue paper comes from the creping process. When the strain goes beyond the elastic region, tissue paper changes irreversibly, and a slower increase in force is achieved with an additional increase of strain. Force increases to a point where the strength reaches a maximum, called the tensile strength, and this is followed by the failure of the tissue paper at the weakest point. The area calculated below the stress and strain curve represents the energy absorbed by the sample during the tensile test (Thorp 1991). The energy absorbed is an important property for tissue products. Those products are usually designed to have low density to maximize softness and absorbency. As a result, bonding among fibers is not as well developed as it is in the case of other paper products (*e.g.* printing, packaging). However, tissue products have to be strong enough to withstand papermaking, converting, and use. Even though those products do not present very high tensile strength (maximum force before failure), they are manufactured to have high elongation capacity, which will give them the capacity to absorb energy during various conditions.

Wet Strength

Paper structure and strength are highly dependent on the level of molecular bonding (hydrogen bonding) among fibers. Due to the hydrophilic behavior of cellulosic fibers, inter-fiber hydrogen bonds are not resistant to moist conditions. However, as mentioned earlier, some tissue products, such as kitchen and hand towels, need to be moisture resistant to be capable of drying and cleaning wet surfaces. In order to maintain some of their strength when wetted, wet strength additives can be used to supplement or replace hydrogen bonding (Hubbe 2014). Wet strength performance of paper products depends on having a coherent network of fibers reinforced with a crosslinked network of wet strength additives that repress fiber swelling and inhibit fiber-fiber separation. Some wet strength additives, such as urea-formaldehyde, will self-crosslink, forming an insoluble network around contacts among fibers that preserves some of the original dry strength. Besides self-crosslinking, other additives, such as azetidinium resins, will form water-resistant covalent bonds in the cell wall of fibers or between fibers that will reinforce fiber bonding (reinforcement mechanism) (Espy 1995). The content of fines in the furnish is an important variable because cationic wet strength additives will be preferentially adsorbed on fines, and high levels of fines can be a problem limiting high wet strength performance (Nanko *et al.* 2005). Typically, if a paper product can retain more than 15% of its dry strength, it can be regarded as a wet-strength grade. Efficient wet strength additives can retain up to 50% of the dry strength. Besides paper strength improvements in wet conditions, those wet strength additives are known to increase dry strength (Lindström *et al.* 2005).

Softness

Softness can be defined as a human sensory response to a texture that is pleasing to touch and provides a feeling of delicate and smooth texture lacking stiffness. In other words, softness is the sensory response obtained when someone strokes the surface with fingers and crumples the tissue by hand. Perceived softness is a result of a combination of several sensorial reactions, including not only tactile perception, but also the audio and visual (color, embossing) perceptions. Softness is a very important property, especially in sanitary applications, where consumers are very sensitive to softness acceptance. Softness is usually divided into surface softness and bulk softness. Surface softness is related to the velvet-like feeling of the paper surface that is perceived by human fingerprints, which depends on fiber type, smoothness and finishing of paper surface (*e.g.* addition of softeners/lotions, wire marks, creping, embossing). Short and flexible fibers are desirable for surface softness. Bulk softness is an indication of how easily the paper yields when crumbled, which depends on paper stiffness, bulk, and the ability of fibers to move within the fiber web. Bulky and flexible fibers with low bonding ability are desirable for bulk softness (McKinney 1995; Bhatia *et al.* 2004; Hollmark and Ampulski 2004; Liu 2004; Kullander 2012).

Human panels are traditionally used to access softness. The results obtained can be considered as being subjective to the group of people involved in the study, which could be paper specialists or consumers. Because different individuals have different opinions and sensitivity to softness, a large number of people and testing is necessary to obtain valid results. To reduce time and resources, many analytical methods involving physical measurements related to surface or bulk properties have been developed to access softness. Basis weight, thickness, bulk, flexibility, stiffness, compressibility, elongation (stretching), draping, crumple, penetration, sound emission, sound attenuation, and thermal conductivity are some of the bulk properties evaluated in the literature. Some of the surface properties evaluated include smoothness, friction, roughness, and fiber free ends. Yet, there is not an acceptable analytical method that can be used to fully mimic the human perception of softness. Analytical methods that combine measurements related to surface and bulk properties usually have better performance (Bhatia *et al.* 2004; Hollmark and Ampulski 2004; Kullander 2012).

High bulk paper products tend to have superior bulk softness because bonding strength and bonding area among fibers are not as fully developed. The creping process softens the paper by improving the bulk softness when fibers bonds are broken and sheet extensibility is improved. Creping can also increase the surface smoothness. The number of plies also tends to increase bulk softness (Boudreau 2013). Calendering can be used to improve surface smoothness (Novotny 1988). Tissue products made with low coarseness fibers having a large number of free and flexible fiber ends protruding up from the surface present better surface softness. Fibers having higher coarseness are more desirable to give better bulk softness (Kim *et al.* 1994; Axelsson 2001). Higher softness is achieved with the use of curly fibers (Trepanier 2017). Sulfite and kraft pulps are softer than recycled and mechanical pulps (Novotny 1988).

TISSUE FACILITIES AND MACHINE TECHNOLOGIES

Tissue Facilities

Tissue products are manufactured in facilities having different configurations and levels of integration. Tissue facilities can be differentiated in terms of pulping and recycling capabilities (integrated and non-integrated) and fiber type (virgin and recycled). Integrated facilities have assets for on-site pulp production and tissue manufacturing. In those mills, the starting raw material can be wood or non-wood when tissue is manufactured with virgin pulps or recycled paper in the case of recycled tissue production. Usually, virgin integrated facilities are more complex, having all the assets necessary to convert wood and non-wood into the paper (*e.g.* pulping, washing, bleaching, stock preparation, paper machine, chemical recovery, steam and power production, and effluent treatment). Due to process capabilities and high level of process integration, it is common to have virgin integrated facilities that produce not only tissue products but also market pulp and other paper products. Recycled, integrated facilities have the assets to reprocess recycled paper into tissue products (*e.g.* hydro pulping, washing, deinking, bleaching, stock preparation, paper machine, steam and power generation). Non-integrated facilities do not have any pulping or recycling capabilities. The starting raw material is market pulp (virgin or recycled fibers), and the process configuration is simpler (stock preparation, paper machine, steam, and power production). Recycled integrated and non-integrated facilities are usually more dedicated plants, although facilities that also produce other paper products can be found (FisherSolve International 2017).

Tissue Machine Technologies

The final properties of tissue products are highly dependent on the tissue machine technology. Light Dry Creped (LDC) (Fig. 1) is the most conventional technology. The main differences between an LDC machine and a conventional, non-sanitary paper machine are the shorter length, Yankee cylinder drier (large steam heated drum), and creping processes. Headboxes used in tissue machines are designed for low consistencies (0.1% to 0.5%), and they are similar to headboxes used in conventional paper production.

The basic purpose of a headbox is to evenly distribute the stock on the forming fabric (often called the “wire”) and prevent fiber flocculation by applying turbulence to achieve relatively uniform paper formation. Control of fiber orientation is performed by adjusting the ratio of jet speed and wire speed (Kullander 2012). Headboxes can also be layered to allow for distribution of different types of furnishes in the center and surfaces of the paper web (Tysén 2014). For example, the internal layer can be made with long fibers (softwoods) to provide strength, machine runnability and bulk softness, while the external layer can be made of short and thin fibers (hardwoods) to improve surface softness (Axelsson 2001; Pavan 2011).

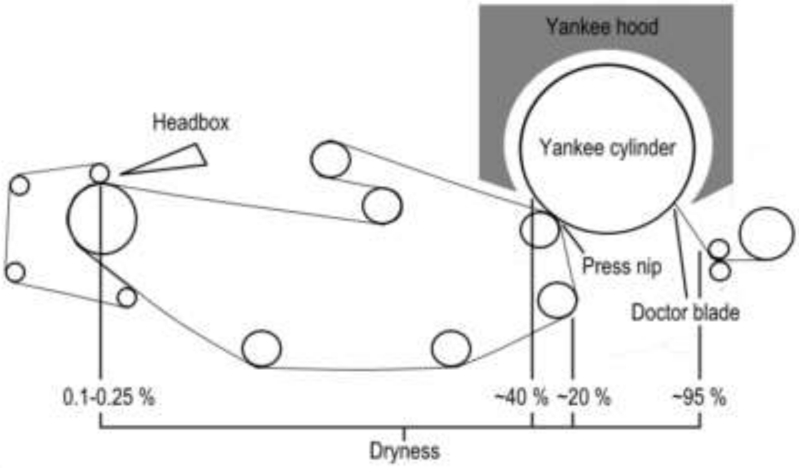


Fig. 1. Sketch of light dry crepe (LDC) tissue machine composed by a crescent former, pressing section, Yankee cylinder and creping blade (Tysén 2014)

There are four main types of forming section used in tissue machines, crescent former, twin-wire, suction breast roll, and Fourdrinier. Nowadays, the most common forming section for tissue grades is the crescent former (Fig. 1), where the stock jet is directed between a forming fabric that promotes the drainage and a felt. Crescent formers provide superior runnability at high speeds (up to 2400 m/min) because no transfer between wire and felt is needed. The second most common forming section is the twin-wire (2000 m/min), where the stock is sprayed in between two wires, promoting efficient dewatering and good control of fiber orientation. In a suction breast roll former (up to 1500 m/min), dewatering is controlled by suction, such that water is drained from the space between the top of the headbox and the wire. A suction breast roll former does not allow good control of fiber orientation. The last and oldest type of forming section is the Fourdrinier former. The Fourdrinier is limited in speed (up to 1000 m/min) and dewatering happens in one direction through the web by gravity and suction (Pavan 2011; Kullander 2012).

Vacuum systems, such as suction boxes or suction rolls, are usually used to increase the consistency to the range of 15% to 25%. Before the LDC drying step at the Yankee cylinder, the paper web is pressed at the press nip (2 to 4 MPa) by a roll press or shoe press to reach a consistency of 40% to 45%. The shoe press has a longer nip and applies lower pressure than a roll press roll, resulting in a bulkier web. The level of pressure used at the press nip is crucial. Minimum pressing is desired for the production of a higher bulk and soft tissue. After pressing, the paper web is dried at the surface of Yankee drier up to a solids content of 94% to 98%. The drying process is performed by the steam-heated Yankee cylinder surface and by hot air flow from the hood above and surrounding the Yankee cylinder (Kullander 2012). A coating is sprayed on the Yankee surface to promote the adhesion between the sheet and the Yankee and to protect the metal surface of the Yankee from the creping blade (Forbess 1997).

The creping process is a very important step for the production of tissue products with higher bulk, absorbency, softness, and stretch. During the creping process, the doctor blade scrapes the paper web off from the Yankee surface. Creping delaminates the internal physical structure of the paper web, forcing the fiber bonds to be weakened/broken and forcing the fibers to buckle, become distorted or even broken. Micro-folds also are created and piled up on top of each other, and when the pile is high enough, it falls and creates a macro-folded and structured end product (Fig. 2) (Kullander 2012; Peters 2016). The delamination process tends to produce a thicker, more absorbent, and cushiony tissue product with higher water-holding capacity than does the folding type of creping (Nanko *et al.* 2005).

Good adhesion between the Yankee surface and the paper web results in a finely creped product that is bulkier, more absorbent, and softer. Good adhesion promotes the proper breakage of fiber bonds and higher frequency of creping folds. Additionally, more fibers are pulled from the paper surface creating more fiber ends that enhances the hand feel (Boudreau 2013). High adhesion might cause defects or web breaks. Low adhesion may result in low creping frequency and low quality (Sundholm and Huostila 1980). Good adhesion is achieved with pulps having better bonding ability (Zou 2017b). Refined pulps having higher hemicellulose and higher fines content will promote better adhesion. A tissue web having higher basis weight and higher moisture will also present better adhesion to the Yankee surface (Boudreau and Germgard 2014). Kraft pulps gives the best adhesion, followed by sulfite and mechanical pulps (Novotny 1988). Among different mechanical pulps, chemi-thermomechanical pulps (CTMP) have better adhesion to Yankee dryer than Thermomechanical Pulp (TMP) and Groundwood Pulp (GWP) (Sundholm and Huostila 1980). Typically, the Yankee side of the tissue paper is softer than the felt side. The Yankee side has small valleys that give a softer sensation, while the felt side has peaks that provides a rougher sensation. Therefore, it is recommended to put the Yankee side of the sheet on the outside of tissue products (Boudreau 2013).

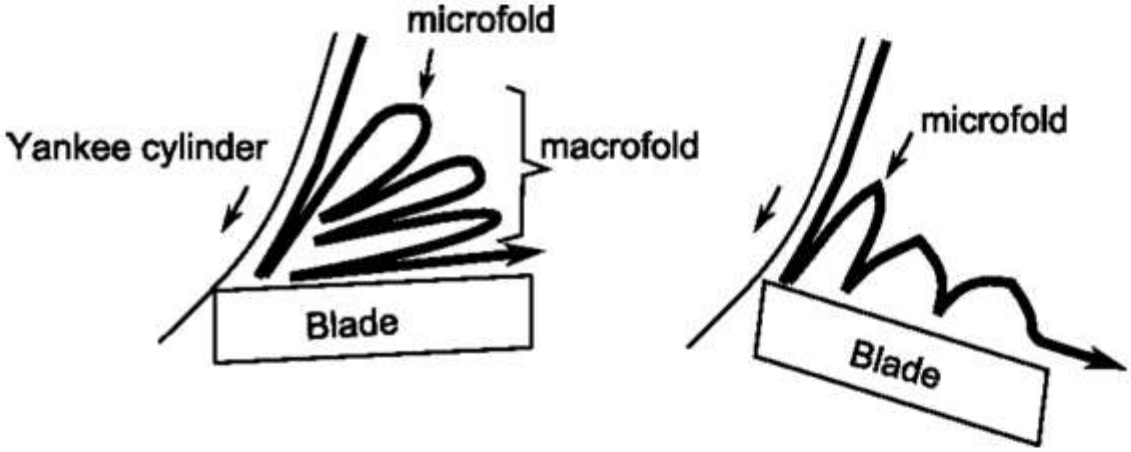


Fig. 2. Creping process and the formation of micro-folds and macro-folds as a function of the angle between the top surface of the creping blade and Yankee surface. Left: small angle. Right: large angle (Raunio and Ritala 2012).

The angle between the top surface of the blade and the surface of the Yankee drier influences the amount of micro- and macro-folds created in the tissue paper. Values between 40 to 100 degrees are observed, especially in the range of 80 to 90 degrees. Smaller angles creates higher number of macro-folds (piles of micro-folds). This creping process yields a super creped product that is unusual. At higher angles, the macro-folds are not significantly formed (Raunio and Ritala 2012).

Another important paper machine technology used for tissue manufacturing is the Through-Air Drying (TAD) process. Different from the dry creped machine, the TAD machine does not have a press section, and this helps to preserve the three-dimensional structure of the paper web. Dewatering before the drying section is achieved with vacuum on suction boxes to a consistency of about 20% to 25%. The paper web is transferred to a perforated through-air drying cylinder, where hot air is blown through the tissue web. An imprinting TAD fabric can be used to imprint a knuckle pattern on the tissue web. (Sanford and Sisson 1967). Usually, the imprinting is performed by sucking the tissue web against the TAD fabric, before the through-air dryer and while the tissue web is in a wet state. In a through-air dryer, the hot air can be blown to the web from the inside of the cylinder or from the outside of the cylinder while the imprinted structure is maintained (Klerelid 2002). As a result of the low level of pressing and through-air drying, the final tissue product has higher bulk, softness, and absorbency, which makes TAD an ideal technology for the production of premium and ultra grades (Sanford and Sisson 1967; Klerelid 2002). However, a TAD machine has higher energy costs (gas and electricity) and around three times higher capital costs than a conventional machine (Kullander 2012).

In the Creped Through-Air Drying machine (CTAD) (Fig. 3) the through-air system dries the tissue web until a consistency of about 40% to 80%. The partially dried web is finally transferred to a Yankee cylinder, where it is fully dried to about 96% consistency and creped (Sanford and Sisson 1967).

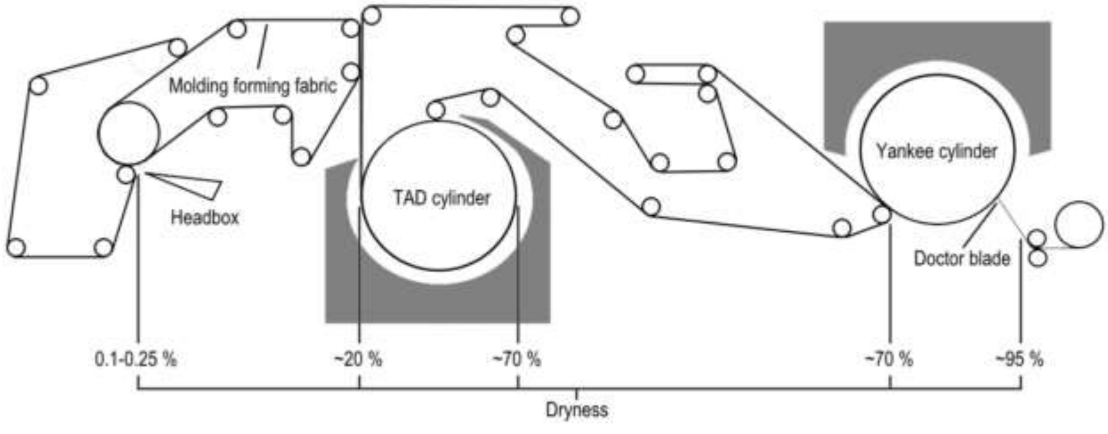


Fig. 3. Sketch of creped through-air drying (CTAD) tissue machine composed by twin wire former, through-air dryer, Yankee cylinder and creping blade (Tysén 2014)

In early CTAD processes, the weave of the TAD fabric molds the sheet and then the knuckles contact the Yankee, but leaving the pillows un-compressed. This sets a coarser creping pattern on the Yankee (Fig. 4). The pillows remain as absorbent capillary bundles, as compared to the compressed knuckle areas, resulting in a product with good tensile strength but having better softness and absorbency relative to dry crepe tissue paper (Table 4) (Sanford and Sisson 1967).

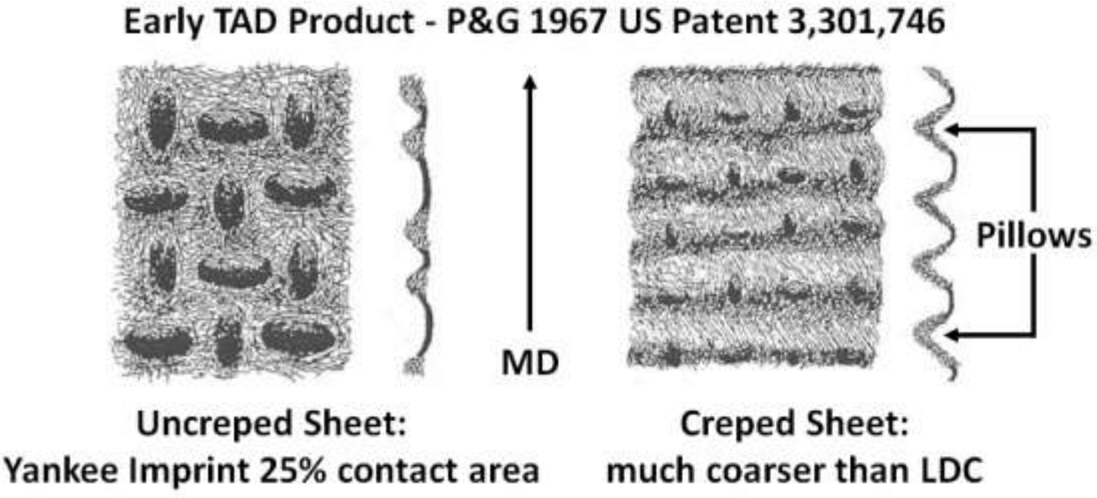


Fig. 4. Early TAD tissue product (MD = machine direction) (Adapted from Sanford and Sisson 1967)

More recently, other types of paper machines technologies have been developed, especially in the USA market, such as UCTAD (un-creped TAD), DRC (double re-crepe), ATMOS (Advanced Tissue Molding System), and NTT (New Tissue Technology). UCTAD was developed to decrease limitations in tissue machine speed caused by variable crepe in the TAD process at higher speeds (Fig. 5). The formed sheet is transferred to the molding fabric at about 22% consistency and then on to the TAD dryer to dry to 97% solids content. The lack of a creping process initially resulted in a harsher sheet, but recent advances in surface treatments have ameliorated that (Wendt *et al.* 1998).

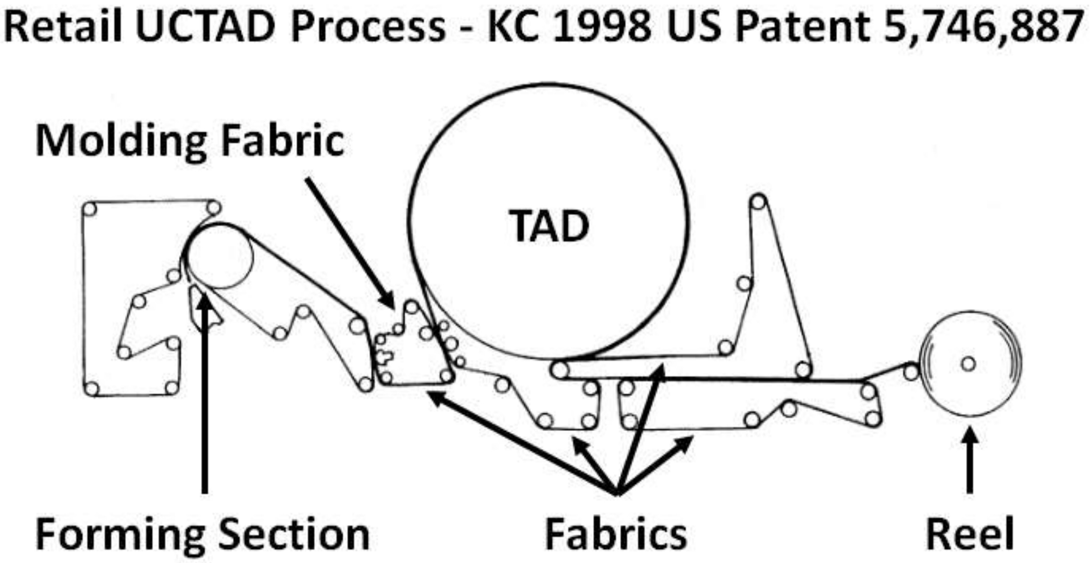


Fig. 5. Un-creped through-air drying (UCTAD) tissue machine composed by twin wire former and through-air dryer (Adapted from Wendt *et al.* 1998)

Table 4. Comparison between Early TAD Products and Conventional or Dry Crepe Products

Properties	Products	TAD	LDC	TAD/LDC
Dry Density (g/cm^3)	Towel and Bath	0.08	0.14	0.6
Dry CD Stretch (%)	Towel and Bath	12	6	2
Wet/dry thickness ratio (-)	Towel	-	-	1.6
Softness (-)	Towel and Bath	-	-	2.2
Absorbency Capacity (g/g)	Towel	23	14	1.6
Absorbency Rate (g/sec)	Towel	0.5	0.2	2.5

DRC was developed to produce a product that is similar to a two-ply product from a single tissue sheet (Fig. 6). The process is similar to an LDC machine prior to Yankee #1, but then it is creped at 70% consistency (called wet-creped) to delaminate the formed layers, and then imprinted with a latex scrim on each side before sending to Yankee #2 for creping on the other side. This process produces a very soft surface feel but is very expensive (Gentile *et al.* 1975).

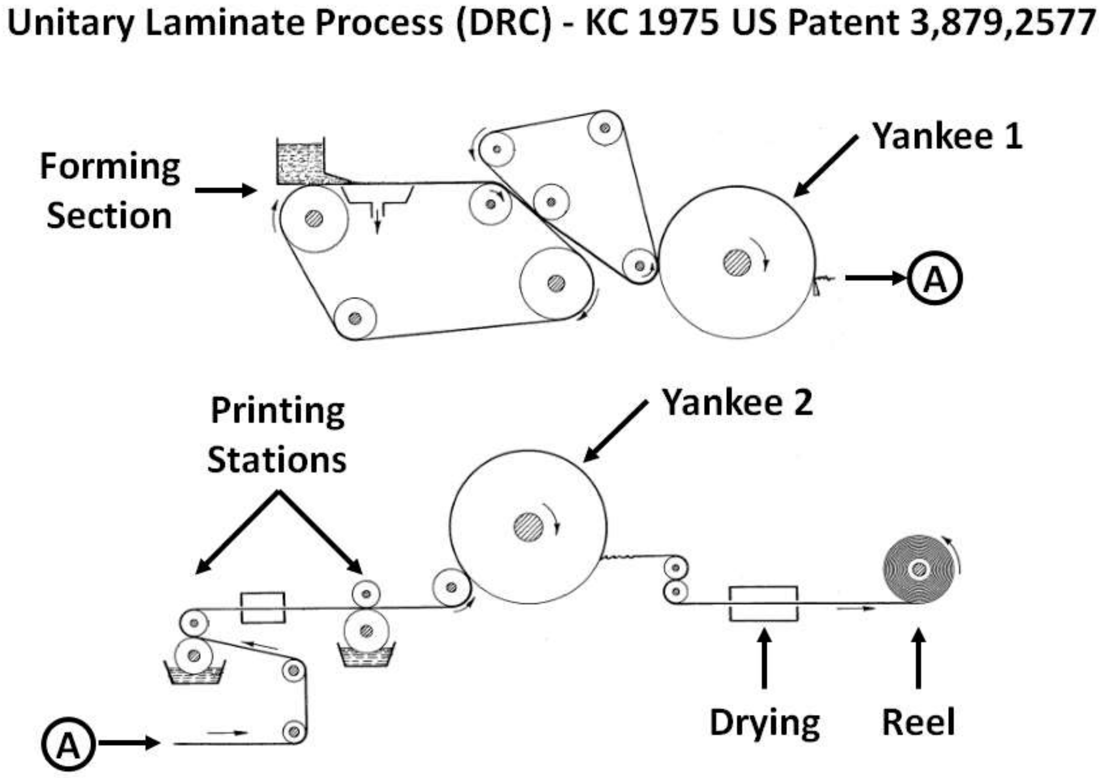


Fig. 6. Double re-cepre (DRC) tissue machine composed by a fourdrinier former, two Yankee cylinders and latex imprinting stations (Adapted from Gentile *et al.* 1975).

ATMOS was developed in the early 2000's (Fig. 7). The goal of the newer, more energy efficient process is to use mechanical means to dewater the sheet to 34% to 38% prior to contacting the Yankee with 25% of the sheet as is done with CTAD processes. Transferring at such low consistencies to the Yankee with only 25% contact area puts a significant burden on the Yankee Hood, which must operate at very high temperatures to achieve competitive speeds (Voith, n.d.).

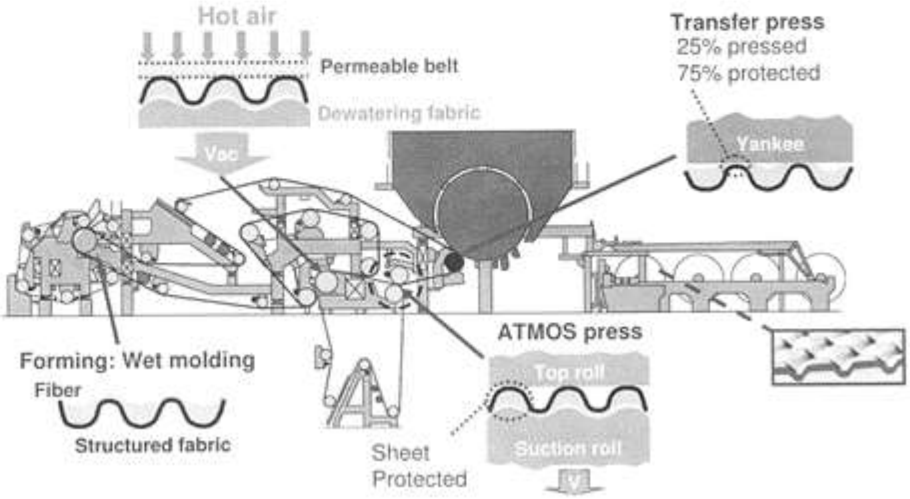


Fig. 7. Advanced tissue molding system (ATMOS) tissue machine (Voith, n.d.)

NTT was designed to overcome some of the limitations of ATMOS by pressing at even higher pressures before transferring to the Yankee (Fig. 8). A shoe press is used in the first pressing section between the Crescent Former felt and a belt with cells designed to provide absorptive capacity and increase strength. Initial production has indicated the ability to achieve up to 45% consistency before transferring to the Yankee, which has reduced the Yankee Hood drying load as compared to ATMOS. However, the high pressures compress the "pillows" of the sheet, which have decreased absorptive capacity as compared to CTAD (Valmet 2014).

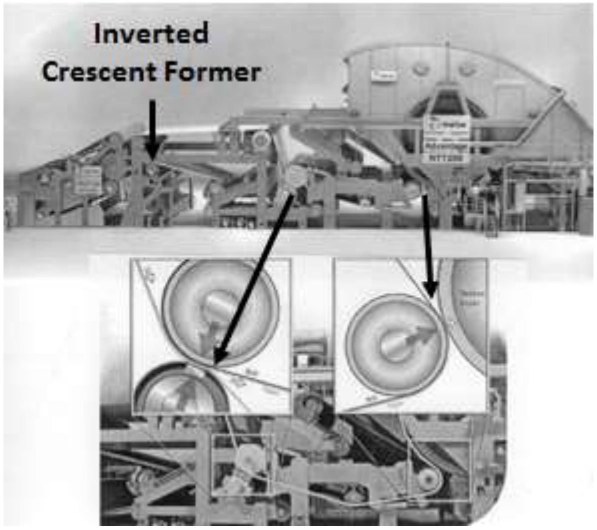


Fig. 8. New tissue technology (NTT) machine (Valmet 2014)

In the late 1980's, Procter & Gamble patented a belt to replace the fabric in CTAD. It has the advantage of designing the structure of the molded tissue based on the product's intended use. The initial belt for a kitchen roll towel is shown in Fig. 9. The lower left schematic is a side view of the belt. It shows a woven "secondary" fabric for belt strength inside a cast urethane belt. A photosensitive urethane resin is extruded around the woven fabric, and the desired pattern is developed by catalyzing the areas that are to remain on the belt. The picture on the right shows one version of the belt after casting. One can see the individual cells for absorbency as well as the secondary fabric that is now part of the belt. The result is a molding belt that provides uncompressed pillows of fiber while also providing lines of high compression that are pressed against the Yankee for tissue strength. This is analogous to replacing the "spot welding" provided by the woven fabric with "continuous welding" with the belt (Smurkoski *et al.* 1992).

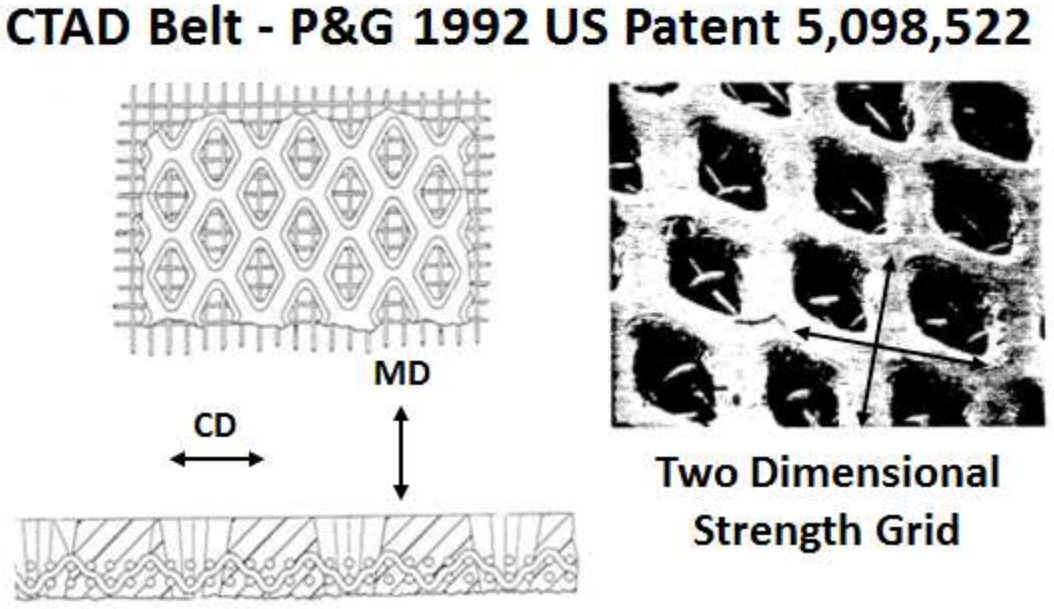
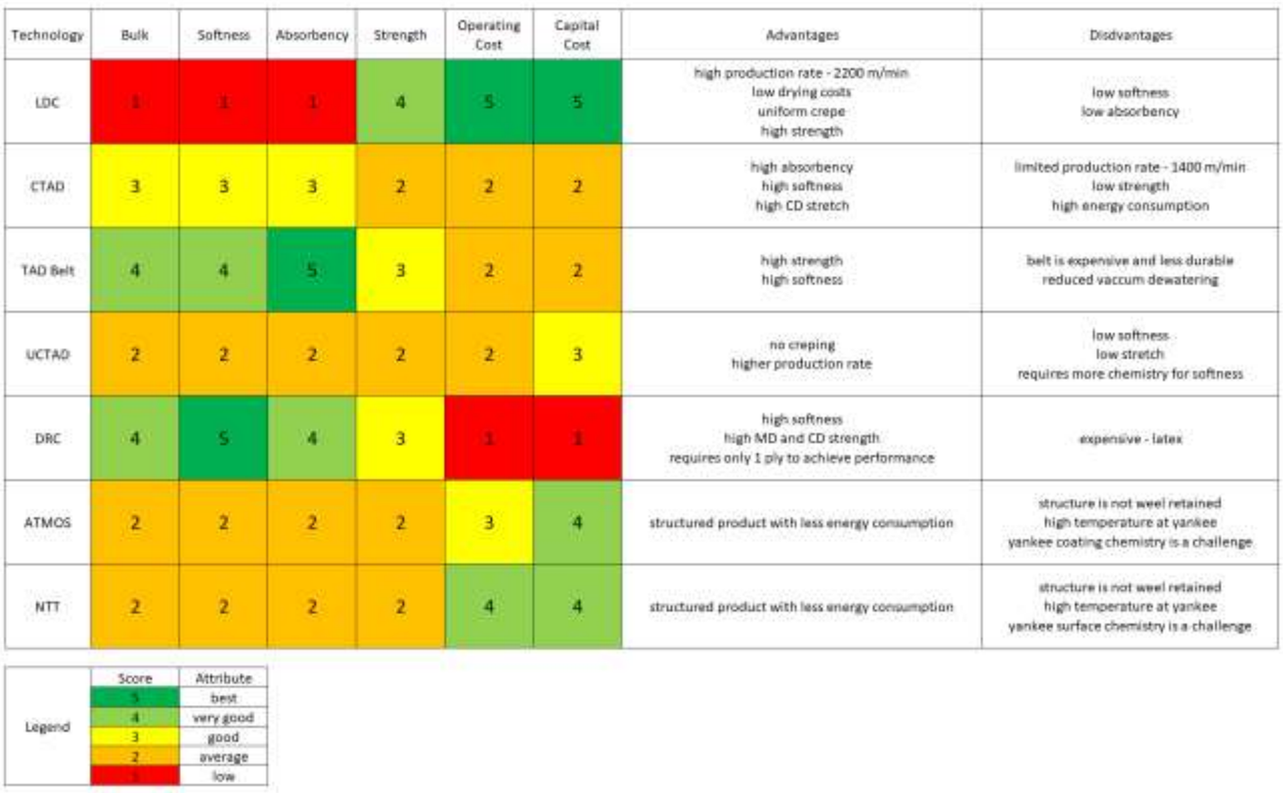


Fig. 9. CTAD belt used to manufacture kitchen towel (Adapted from Smurkoski *et al.* 1992)

When the various technologies above are compared to each other, they have their advantages and disadvantages as shown in Table 5.

The final step in the tissue manufacturing is the converting process. Converting includes several processes (unwinding, embossing, printing, perforation, winding and tail sealing, log sawing, folding, wrapping, and packaging). Products with two or more plies have inter-ply space, which contributes to higher absorbency capacity. The number of plies also improves tissue strength and softness. The tissue plies are pressed together completely or just at the edges during the embossing process. Embossing is the process where tissue sheet passes in between two engraved steel or rubber rolls having a matched pattern that provides texture to the sheet. During the conversion of tissue having multiple plies, embossing can be applied to each ply separately that are later glued together. The plies can also be embossed simultaneously. The simultaneous embossing can be performed in a foot-to-foot or nested configuration. In the foot-to-foot configuration, the embossing patterns of both plies are aligned to each other, resulting in the creation of suction pockets with superior water absorbency. In the nested configuration, the embossing patterns of one ply are positioned in between the embossing patterns of the other ply. In other others, the "valleys" of one ply fits the "bumps" of the other ply in the nested configuration (Brown 1991; Enderby and Straten 2001; Kullander 2012). Printing is done for appearance purposes and perforation makes the sheets easier to separate. Some final products, such as bath tissue and kitchen towels, are wound onto a paper core and sealed at the tail. After the winding process, the formed rolls are cut into the desired width (10 to 60 cm). Folding is performed on products that are commercialized as individual sheets, such as, facial tissue and paper towel. Packaging is the final converting step in which the products are wrapped in plastic, paper, and boxes (Kullander 2012).

Table 5. Comparison Among Different Tissue Machine Technologies Highlighting Differences in Products Attributes and Machine Performance (Adapted from Reisinger 2016)



Technology	Bulk	Softness	Absorbency	Strength	Operating Cost	Capital Cost	Advantages	Disdvantages
LDC	1	1	1	4	5	5	high production rate - 2200 m/min low drying costs uniform crepe high strength	low softness low absorbency
CTAD	3	3	3	2	2	2	high absorbency high softness high CD stretch	limited production rate - 1400 m/min low strength high energy consumption
TAD Belt	4	4	5	3	2	2	high strength high softness	belt is expensive and less durable reduced vaccum dewatering
UCTAD	2	2	2	2	2	3	no creping higher production rate	low softness low stretch requires more chemistry for softness
DRC	4	5	4	3	1	1	high softness high MD and CD strength requires only 1 ply to achieve performance	expensive - latex
ATMOS	2	2	2	2	3	4	structured product with less energy consumption	structure is not weel retained high temperature at yankee yankee coating chemistry is a challenge
NTT	2	2	2	2	4	4	structured product with less energy consumption	structure is not weel retained high temperature at yankee yankee surface chemistry is a challenge

	Score	Attribute
Legend	5	best
	4	very good
	3	good
	2	average
	1	low

TISSUE PAPER FIBERS

Different fiber types are available in the market for tissue production, and they can be defined according to their source (virgin or recycled), type of process (chemical, mechanical, semi-chemical, bleached, unbleached), type of biomass (hardwood, softwood, non-wood), and biomass species. All those variables will influence the characteristics of the fibers and properties of tissue products. A vast mixture of hardwoods (eucalyptus, northern, southern, tropical), softwoods (northern, southern), and non-woods (straw, bamboo, bagasse) are used for tissue manufacturing. The main sources of recycled fibers are papers originated from offices (SOP - sorted office paper), magazines (OMG - old magazines), newspapers (ONP - old newspaper), boxes (OCC - old containerboard; DLK - doulble lined kraft), and other mixed recycled papers (MP - mixed paper) (FisherSolve International 2017).

Hardwood and Softwood Pulps

Paper products are usually manufactured with a blend of hardwoods and softwoods. There are two main types of softwood pulps in the USA, southern and northern. Southern softwood pulps are mostly produced from southern pines and radiata pine. Northern softwood pulps are produced from a variety of species (pines, spruces, firs, hemlocks, cedars, Douglas-firs, larches). On the other hand, hardwood pulps are made from a much more diverse group of species and can be divided into two categories, single species, and mixed species. Hardwood pulps will range from 100% aspen, maple or birch to mixed northern or southern species and 100% eucalyptus. Some examples of hardwood pulps include: a) Northern hardwoods: aspen, maples, birches, beech; b) Southern hardwoods: gums, oaks, poplar, ash, beech; c) *Eucalyptus* species including: *grandis*, *urophylla*, *globulus*, *camaldulensis*, and hybrids; d) Tropical hardwoods: acacia, mixed tropical) (Nanko *et al.* 2005). The benefits of hardwood pulps made of single species, such as eucalyptus in Brazil, have caught the attention of the pulp and paper industry. Brazilian eucalyptus trees are harvested from well-monitored plantations, resulting in a very uniform furnish having narrow particle size distribution and low content of fines. Those characteristics allow better control of paper characteristics and papermaking process, including easier drainage and drying, which are usually limiting factors for high speed tissue machines (Hall 1983; Pavan 2011). The third main type of pulp is mechanical pulps, such as chemi-thermomechanical (CTMP), which have a balance of properties from hardwood and softwood species (Fig. 10) (Nanko *et al.* 2005).

Softwood pulps have long fibers that provide a strong fiber network to increase wet web strength and runnability of the paper machine and subsequent converting operations. Softwood fibers are primarily used as reinforcement fiber in many different paper grades, including tissue products. A strong and continuous fiber network is achieved with softwood fibers that are thin and long (low coarseness to length ratio). Due to its low coarseness to length ratio, NBSK is highly desirable as a source of long fibers and strength without loss of softness that comes with other softwoods (Byrd and Hurter 2013). Softwood pulps containing low amounts of fines will contribute to maximize the performance of long fibers, minimize chemical usage, lower drainage resistance, increase retention, and reduce paper dusting. Additionally, softwood pulps with higher fiber strength can maximize paper strength, however, tissue products usually require relatively low tensile strength, and fiber strength is not a critical issue. Softwood fibers with a thick cell wall are less likely to collapse during papermaking process and more prone to form thicker and bulkier tissue products with improved structure openness and water absorbency (Nanko *et al.* 2005). However, softwoods that are finer having thin cell wall are flexible and capable of providing good softness (Zou 2017a). Higher stretch values are also desired in softwood fibers because they improve paper web runnability and result in lower stiffness and higher softness, although most of the stretch observed in tissue products comes from the creping process. Tissue products made of softwood pulps with low bonding strength are more prone to delamination during the creping process, resulting in a bulkier and softer structure. Higher freeness is better but not a major issue because pulp freeness is already high enough in softwoods. Softwood pulps with high unrefined strength are preferred to maximize bulkiness and achieve desired strength (without or with minimum refining) at same time (Nanko *et al.* 2005).

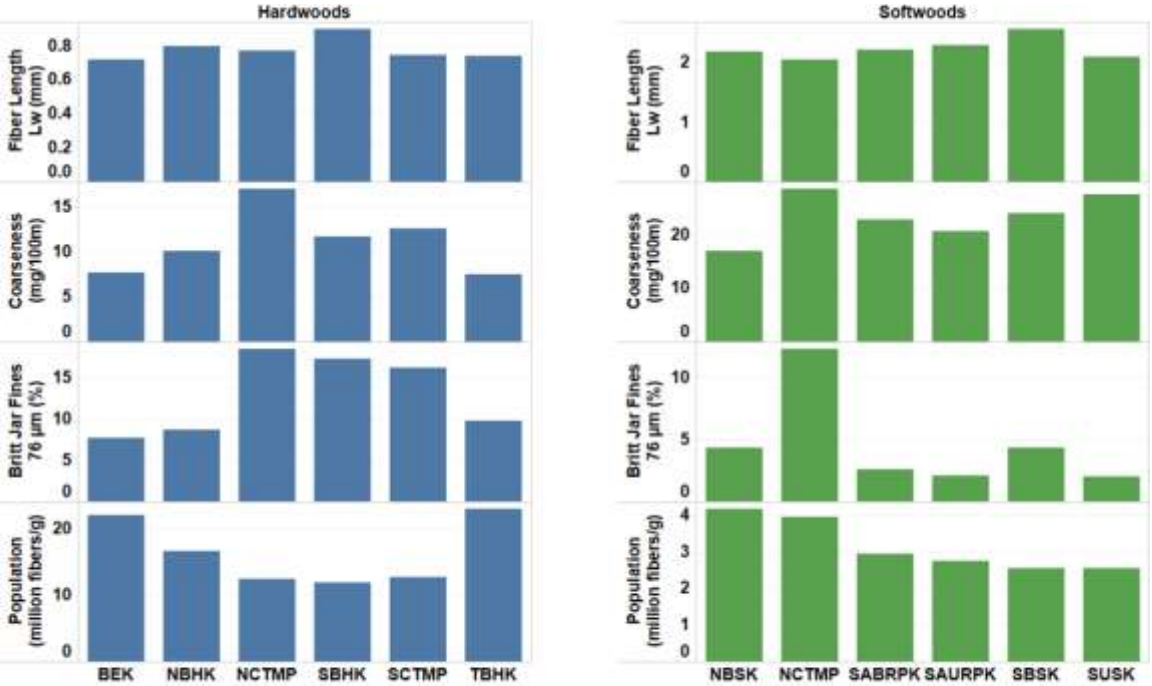


Fig. 10. Morphology of unbleached hardwood and softwood market pulps. BEK: bleached eucalyptus kraft; NBHK: northern bleached hardwood kraft; NCTMP: northern chemithermomechanical pulp; SBHK: southern bleached hardwood kraft; SCTMP: southern chemithermomechanical pulp; TBHK: tropical bleached hardwood kraft; NBSK: northern bleached softwood kraft; SABRPK: South American bleached radiata pine kraft; SAURPK: South American unbleached radiata pine kraft; SBSK: southern bleached softwood kraft; SUSK: southern unbleached softwood kraft (Adapted from Nanko *et al*. 2005)

Hardwood pulps are primarily used for their ability to provide good formation, a smooth surface, finer pore structure, and high opacity. In tissue products, hardwood fibers also provide bulk, softness, and a velvet type surface feel. Hardwood pulps are used in most tissue grades at levels ranging up to 100%, but more typically 50% to 80% of the fiber furnish (Nanko *et al*. 2005; Zou 2017). To develop strength without losing softness provided by hardwoods, refining can be applied only on softwoods (McKinney 1995). Among different types of hardwood pulps, eucalyptus pulp is capable of achieving tissue with high bulk, absorbency, and softness (Byrd and Hurter 2013). Eucalyptus pulp has low fines content, a high population of short fibers with thick cell wall, and low coarseness, which complement the softwood matrix by providing sufficient strength with many free fibers ends to give a soft velvet feel preferred by consumers. The high fiber population of eucalyptus fibers provides a uniform paper structure that facilitates uniform drying (Hall 1983; Nanko *et al*. 2005). On the other hand, high fiber population results in limitations for papermakers in terms of fiber retention on machine wire and dusting and linting in converting operations (Nanko *et al*. 2005). As reported by Foelkel (2007), to achieve high bulk, tissue makers should seek eucalyptus pulps having: a) high coarseness to minimize fiber collapsibility and sheet densification; b) low content of fines to avoid densification, build up in the paper machine white water, and reduction in drainability; c) low hemicellulose content for reduced bonding ability; and d) high fiber deformation (*e.g.* curl, kinks) to improve bulk, sheet porosity and absorbency. Another advantage of eucalyptus pulp is the low content of extractives, which results in improved absorbency and lower deposition of extractives on paper machine. At the same drainage rate, eucalyptus fibers provide good wet web strength when compared to other hardwoods. Eucalyptus is suitable for the production of high quality tissue paper, for which light refining is recommended (22 < Schopper Riegler degrees < 35). The content of eucalyptus in those products can vary from 50% to 60% in napkins, bath tissue and towels to 100% in facial tissue (Hall 1983).

Mechanical pulps can be used to provide increased void volume (bulk) and water holding capacity to tissue products. The higher content of lignin gives mechanical pulps a more rigid structure in the wet state when compared to low yield pulps, which contributes to maintaining the water holding capacity (Nanko *et al*. 2005; Yuan *et al.* 2016). On the other hand, a high content of fines present in mechanical pulps will increase the density of tissue paper and give problems with dusting and linting (Axelsson 2001). A self-sizing mechanism can reduce absorbency rate during storage. Peroxide bleaching can be used to overcome the self-sizing phenomenon and improve absorbency rate due to reduction of extractives content. Peroxide-bleached mechanical pulps also have higher brightness, lower fiber stiffness, better fiber bonding, lower dusting, better brightness stability, and lower slushing time (Johnsson 1978; Norwegian Pulp and Paper Research Institue 1983). Mechanical pulps have small impact in bulk softness but a negative effect on surface softness. In order to minimize the negative impact on softness, it is recommended the use of mechanical pulps having the least amount of shives (Norwegian Pulp and Paper Research Institue 1983). Because mechanical pulps lack the desirable properties for tissue products (*e.g.* softness, strength) to some extent, they are usually blended with other fibers for tissue manufacturing. Up to 50% of mechanical pulp can be used in tissue products without significant change in strength (Johnsson 1978). Bulk and absorbency of towel and bath tissue can be increased with fibers blends having from 5% to 30% of mechanical pulps without significant reduction of softness, strength, and brightness. However, brightness reversion can still be a problem (Yuan *et al.* 2016; Zou 2017). A comparison between different types of mechanical pulps for tissue applications shows that CTMP provides better strength than Thermomechanical Pulp (TMP) and Groundwood Pulp (GWP) due to better bonding ability. GWP presents the lowest strength. Better absorbency rate and capacity is expected for CTMP pulp. On the other hand, due to the self-sizing phenomenon, absorbency of TMP and GWP is negatively affected (Sundholm and Huostila 1980; Norwegian Pulp and Paper Research Institue 1983). TMP is softer than GWP (Novotny 1988).

It is important to highlight that the properties observed in tissue products are a result of the morphological and physicochemical characteristics of the fibers used. In other words, fiber composition and morphology are determinant for tissue properties (Muller and Teufel 1973). As it can be seen from Fig. 10, there is a significant difference in morphology among different types of biomass (*e.g.* softwood, hardwood, non-wood). Additionally, pulps coming from different biomass species will also have different morphologies to some extent. For example, different softwood and hardwood pulps produced in different geographic regions from different species have different fiber morphology. Each one of those particular morphological features will defined their performance in different tissue products (Nanko *et al*. 2005; Zou 2017a).

Non-Wood Pulps

Typically, woody biomass is the preferential raw material used for pulp and paper production due to low cost, wide availability, little content of the non-fibrous material, ease of processing, and uniformity (Roncero *et al.* 2003). Although the world production of non-wood pulp in 2016 was only 6.5% of world wood pulp production (FAO 2017b), non-wood biomass has a long history in pulp and paper industry and can also be considered an important source of raw material. Non-wood fibers can be used as an alternative to: a) provide local raw material security against imported market pulp, b) develop "green" products for consumers with environmental preferences, c) minimize environmental pressure and impacts related to handling of agricultural residues (*e.g.* burning and landfill practices), d) develop local markets where wood fibers are scarce and expensive, e) reduce pulp costs where non-wood biomass is abundantly available and cheap, and f) improve desired properties or give different characteristics to paper products (Byrd and Hurter 2013; Phillips *et al.* 2015a,b; Zou and Liu 2016). For example, in Europe and the Americas, where wood fibers are more readily available than in Asia, the production of non-wood pulp represents only 12.3% and 8.4% of the world production, respectively. On the other hand, Asia, mainly represented by China and India where wood biomass is scarce, produces around 77.4% of world's non-wood pulp (FAO 2017b). However, non-wood fibers are also being used for tissue manufacturing in other regions, such as North America, as a part of sustainability programs (Byrd and Hurter 2013; Zou and Liu 2016).

Non-woods usually provide higher raw material yield than wood and can be obtained from annual plants (planted and harvested annually) or perennial plants (planted once and harvested in multiple years). Non-wood fibers can be obtained from agricultural residues originated from cereal and grain plantations or from fiber crops that are specifically planted as a source of fiber (Byrd and Hurter 2013). Non-wood feedstocks usually have a much wider range of fiber lengths among different species. Many non-wood species, such as straw, bagasse and other agricultural residues, have similar fiber length as hardwoods. Other species, such as flax, hemp and kenaf, have a fraction of long fibers that have to be shortened before papermaking. Some non-woods, such as abaca, flax, hemp, sisal, and kenaf have the same or better properties than softwoods. Regarding morphological features, some substitutes for NBSK include abaca, bamboo, hemp, hesperaloe, kenaf, and sisal, while some substitutes for BEK include bamboo, bagasse, corn stalks, sorghum stalks, and wheat straw. Therefore, careful selection of the raw material is necessary to achieve the desired paper properties, considering the wide range of fiber characteristics found in non-wood biomass. Some of the problems associated with the processing of non-wood biomass are: a) high costs and logistic problems (harvesting, transportation, storage) associated with the bulky raw material, b) control of material decay during the storage in between harvesting seasons, c) high content of silica that makes the chemical recovery difficult, d) poor drainage of produced pulps due to the high content of fines, e) high raw material chemical and physical variability, and f) agricultural residues tend to have low strength. However, some non-woody biomass, such as, bamboo, reed, and switch grass are denser, allowing easier processing and transportation. Additionally, non-wood fibers usually have a lower content of lignin and are easier to pulp (lower temperature and chemical charge). Straw, bamboo, and sugarcane are among the most used sources of non-wood biomass (Leponiemi 2011; Byrd and Hurter 2013; Zou and Liu 2016).

Wheat straw is a byproduct of wheat production. Approximately 3 tons of wheat straw are generated per acre. While about 0.5 tons are necessary to contribute to soil quality and to control erosion, the excess may cause problems with subsequent field operations (*e.g.*, no-till seedling, fungal diseases). Some of the alternatives used to avoid those concerns are the practice of burning the straw and tilling it into the soil. Therefore, wheat straw represents an opportunity for wood fiber substitution. Wheat straw is composed of leaves (9% w/w), nodes (11% w/w), and internodes (80% w/w). Fibers present in each fraction of wheat straw have different fiber length (internodes = 1.20 mm; leaves = 0.79

mm; nodes = 0.65 mm) and number of fine particles (internodes = 24%; leaves = 49% mm; nodes = 51%) (McKean and Jacobs 1997). Moreover, only about 1/3 of the cells in wheat straw are fibers. The remaining cells are non-fibrous cells (vessels, parenchyma cells, epidermal cells) that are shorter (less than 0.5 mm) and wider (up to 150 µm) than fibers (Singh *et al.* 2011). The whole wheat straw has a weighted fiber length around 1.0 mm, with a width around 46 µm having a very low coarseness (4.5 mg/100 m) (McKean and Jacobs 1997). On the other hand, wheat straw fibers have weighted fiber length around 1.2, with a fiber width around 15 to 20 µm (McKean and Jacobs 1997; Singh *et al.* 2011). Wheat straw fibers have high slenderness ratio (fiber length/fiber width = 87), low flexibility coefficient (100 x lumen diameter/fiber width = 42), and high Runkel ratio (2 x cell wall thickness / lumen diameter = 1.4), resulting in a low degree of collapsing and conformability, which gives more porosity and bulk to the paper web. Wheat straw has a high content of extractives, which decreases the pulping yield, and high content of hemicelluloses, which contribute to strength properties (Singh *et al.* 2011). Wheat straw required 1/3 of the refining energy applied to eucalyptus to achieve similar burst and tensile strength and higher bulk. Wheat straw has a much higher drainage resistance due to the high content of fines. Unrefined wheat straw presented 37° Schopper Riegler (SR), which is a higher value than the usual drainage resistance used in tissue machines (25° SR) Roncero *et al*. (2003). Additionally, the high content of primary fines may result in low fiber yield, higher paper density, and lower paper strength. The high content of inorganics found in wheat straw, especially silica, causes problems with chemical recovery and deposits/corrosion of equipment. Preprocessing can be used to separate wheat straw components with less desirable properties (dirt, inorganics, leaves, nodes, pith/parenchyma cells), which will decrease the content of fines and inorganics, and improve pulping yield, recovery process, drainage, and paper strength (McKean and Jacobs 1997).

Sugar cane bagasse is a byproduct of the sugarcane industry. After crushing sugarcane stalks to extract sucrose juice, the remaining fibers are called sugarcane bagasse. Typically, 1 tonne of sugarcane stalks (70% moisture content) generates about 135 kg of bagasse. The majority of bagasse is usually burned inside sugarcane mills to generate steam and power (Bonomi *et al.* 2011). The excess bagasse can be used as a source of fiber for paper products. Around 60% to 70% of bagasse mass is composed of useful fibers. The remaining mass is represented by non-fibrous parenchyma cells (pith) and soluble matter (Agnihotri *et al.* 2010; Lois-Correa 2012). Due to its high content of pith, bagasse has high dewatering resistance and poor paper properties (Rainey 2012). Depithing is a known preprocessing step used to remove the majority of the non-fibrous fibers before pulping. Depithing not only removes non-fibrous material but also reduces the amount of dirt and inorganics and produces paper with better quality (Lois-Correa 2012). Depithing improves dewatering, strength and pulping yield of bagasse (Rainey 2012). The fiber length of depithed bagasse is around 1.5 mm, and they have a width of about 20 µm. Parenchyma cells and vessels have a wide range of particle sizes and are shorter and wider than fibers. When compared to hardwoods, bagasse fibers have high Runkel ratio (2.5), high slenderness ratio (71), and low flexibility coefficient (29), resulting in low flexibility, low fiber bonding, and high bulk. The high content of extractives and ash contributes to lower pulping yield and operating process associated with inorganics. The high quantity of ashes cannot be considered so problematic since the silica-based salts are negligible. High hemicellulose content benefits the paper strength (Agnihotri *et al.* 2010).

Bamboo is a non-wood biomass with a high growth rate (up to 27 OD tonne/year acre) having long and semi-long fibers with properties in between hardwood and softwood fibers. Bamboo has lower content of fines, higher density, and is better resistant to storage degradation than other non-woody biomasses. Bamboo is composed by culms or internodes (most desirable source of fibers), nodes, and branches that rise from nodes and leaves (Phillips *et al.* 2015a). The average length of bamboo fibers is around 2.0 mm. The average width of bamboo fibers is around 18 μm, and fiber coarseness is around 5 to 9 mg/100m. However, the weighted average fiber length of bamboo pulp is reported to be around 1.2 mm due to the high content of short fibers (Nanko *et al.* 2005; Cao *et al.* 2014; Phillips *et al.* 2015a). There are differences in the morphology of fibers found in internodes and nodes. Nodes have much shorter (0.7 mm) and wider (30 μm) fibers than internodes (length = 2.5 mm; width = 11 μm). Nodes have a much higher content of fines. Therefore, the presence of the nodes significantly reduces the average fiber length, which negatively impacts drainage and paper properties. De-knotting before pulping using suitable screening techniques is a process alternative to improve paper quality (Cao *et al.* 2014). Different values for Runkel ratio (1.5 to 3.5), slenderness ratio (70 to 160), and flexibility coefficient (20 to 40) have been reported in the literature (Singh *et al*. 2011; Cao *et al*. 2014). Bamboo has lower lignin content than softwoods and hardwoods requiring milder pulping conditions. The hemicellulose content of bamboo is also higher than wood biomass. Bamboo nodes have a higher content of lignin, inorganics, and silica than bamboo internodes (Cao *et al*. 2014). Bamboo can present pulping yields similar to hardwoods. Bamboo pulps can have fiber properties, such as, fiber length and coarseness, and paper properties, such as, softness, bulk, and strength that area in between the observed properties of hardwoods and softwoods pulps (Byrd and Hurter 2013; Phillips *et al.* 2015b; Zou and Liu 2016).

Virgin and Recycled Fibers

Virgin fibers are fibers that were never converted in paper products and are fresh from wood pulping. On the other hand, reprocessed fibers that have been converted into paper products one or more times are called recycled or recovered fibers. The properties and characteristics of virgin and recycled fibers are different, although most of those differences are subtle. Physical and chemical changes occur as a result of various processes involved during papermaking, paper use, and paper recycling (*e.g.* additives, pressing, drying, printing, storage, converting, repulping, deinking, and bleaching). Detailed reviews on the impact of recycling process on fiber and paper properties were published by McKinney (1995) and Hubbe *et al.* (2007). An overview of these and other works is presented here.

It is expected that a recycled paper would have fibers with a wide range of age or recycling cycles (Göttsching and Stürmer 1978; Hubbe *et al.* 2007). The physical characteristics of recycled fibers change with the number of recycling cycles, reaching a plateau after about four or five cycles of repulping and drying (McKinney 1995; Hubbe *et al.* 2007). However, the first recycling cycle contributes to major changes in the properties of cellulosic fibers (McKinney 1995).

During the papermaking process, a significant portion of wet-end additives tend to remain associated with the fibers even after recycling. A portion of the fillers that are highly present in some recycled paper grades are not completely eliminated during the recycling process (Muller and Teufel 1973). Hydrophobic effects of sizing agents may partially survive after recycling and can reduce the wettability and strength of paper products (McKinney 1995; Hubbe *et al.* 2007). Dry strength additives, such as cationic starch, can still contribute to the strength of paper after recycling. However, the impact of recycled additives in paper properties will practically be eliminated when fibers are recycled multiple times. Wet pressing will decrease water-holding ability due to closure of voids inside the cell wall (McKinney 1995). Irreversible loss of swelling is observed when fibers are pressed at consistencies above 30% to 35% (Maloney *et al.* 1997). The drying process renders a hydrophobic character to cellulosic fibers, and there is a reduction of swellability or hornification (Muller and Teufel 1973; McKinney 1995). This behavior is more pronounced in chemical pulps, especially when they are refined. The porosity, fibrillation, and cell wall delamination of refined chemical pulps are partially reversed during the drying process, which contributes to the reduction in swellability. Because mechanical pulps are not as porous and fibrillated as chemical pulps, their swellability loss caused by the drying process is much less pronounced. Paper drying semi-irreversibly closes nano-sized pores, decreases external surface area, decreases flexibility and conformability, and makes the fibers more susceptible to breakage when they are further refined. Calendering can reduce fiber swelling capacity and fiber damage (McKinney 1995; Hubbe *et al.* 2007). Printing also has a negative effect on recycled fibers. The presence of black or colorful dots in the final product is related to the incomplete elimination of ink fragments during the recycling process (Muller and Teufel 1973; McKinney 1995). Additionally, inks are usually hydrophobic materials that will reduce the bonding ability and increase the cationic demand of fiber furnish (Hubbe *et al.* 2007). Converting processes, such as gluing, will increase the content of contaminants in recycled fibers. High levels of wax, adhesives, and wet-strength agents can cause various problems during the recycling and papermaking process. Deposits on wires, felts and cylinders may cause holes and weak points in the tissue web (Muller and Teufel 1973; Grivas 1992). The storage of paper products at high temperatures will cause embrittlement of fibers and accelerate the decomposition of cellulosic chains (Hubbe *et al.* 2007).

Recycling operations may or may not interfere in the quality of recycled fibers. Mechanical processes executed at high consistencies (*e.g.* pulping, dispersion, bleaching) increases fiber curl which yields a bulkier paper web with reduced strength. The removal of fillers during the recycling process (*e.g.* deinking, cleaning) increases drainage rate, tissue strength, bulk, and absorbency (McKinney 1995). Fiber recycling may reduce the content of hemicellulose, which will hurt the strength of recycled paper. Recycling can also cause redistribution of extractives on fiber surfaces, resulting in lower wetting ability and reduced strength. Despite the high level of energy used during aqueous repulping of recycled paper, little damage to fibers is expected to occur during that operation (Hubbe *et al.* 2007). The use of sodium hydroxide during pulping improves fiber bonding ability due to cleaning of fiber surface and enhancement of fiber swellability (McKinney 1995; Hubbe *et al.* 2007). Deinking processes may have positive and negative effects. Deinking reduces the level of inks, stickies, dirt, and fines, and deinking *per se* does not significantly damage or degrade physical properties of fibers. However, some of the chemicals used during deinking (*e.g.* fatty acids, surfactants, dispersants, bleaching chemicals) will remain with the fibers. Some deinking chemicals can improve inter-fiber bonding by removing oleophilic particles from fibers. Nonionic surfactants used for deinking tend to act as wetting agents (Hubbe *et al.* 2007). Surfactants lower surface tension and reduce the bonding between fibers (McKinney 1995). The use of fatty acids and calcium as deinking chemicals can reduce paper strength and operating efficiency of the paper machine. It is important to point out that generally, the better the cleaning and deinking processes, the better will be the properties of recycled fibers. Cleaner pulps can be achieved with a higher reject rate during cleaning and deinking. In other words, recycled pulps with better properties and operating characteristics can be obtained by sacrificing some of the fiber yield (Hubbe *et al.* 2007).

The papermaking and recycling processes causes surface and bulk changes on cellulosic fibers. Recycled fibers have lower swelling ability and wet-flexibility, especially in the case of once-dried kraft fibers, resulting in reduced inter-fiber bonded area and bonding strength. Recycled fibers are shorter and have higher content of fines than virgin fibers (McKinney 1995; Hubbe *et al.* 2007). Additionally, when kraft fibers are refined before been dried during the papermaking process, a subsequent larger loss in fiber bonding is expected when the same fibers are recycled (Hubbe *et al.* 2007). In the case of mechanical pulps, the recycling process increases the collapsibility and flexibility of fibers, resulting in better inter-fiber bonding and improved paper strength (McKinney 1995; Hubbe *et al.* 2007). Among different types of mechanical pulps, CTMP pulp has a faster response to recycling process than TMP and GWP pulps. CTMP pulp has lower wall rigidity than other mechanical pulps (McKinney 1995).

In order to improve the strength limitations found in recycled fibers, mechanical refining is a common approach used by papermakers. However, refining of recycled fibers has to be considered with caution. Most of the recycled fibers have been refined once, and recycled fibers are expected to be more prone to fragmentation than virgin fibers. Refining of once dried fibers will only recover part of strength lost. Losses of bonding ability are observed even when recycled fibers are refined again to the same level of freeness reached before they were first dried (McKinney 1995; Hubbe *et al.* 2007). When recycled fibers are refined to reach similar strength of virgin fibers, significant decrease in drainage rate is observed (McKinney 1995). The use of high-intensity refining can be expected to exceed tensile strength of some fibers, increase a number of fines and decrease the drainage rate. The use of high consistency refining can be considered a better alternative for refining recycled fibers. High consistency refining will reduce the likelihood of contact between the refiner surface and fibers that tend to cause fiber fragmentation (de Ruvo and Htun 1983). Another usual approach to minimize the limitations of recycled fibers is to blend them with flexible and fibrillated virgin fibers. High pH conditions can also be used to restore the swelling and flexibility of fibers, although this approach will cause significant delignification. Limitations in inter-fiber bonding can also be overcome by wet end additives (*e.g.* cationic starch) (McKinney 1995; Hubbe *et al.* 2007).

Recycled fibers generally contribute to reduced bulk and surface softness when compared to virgin fibers. Recycled fibers are stiff and are not able to provide the desired flexibility necessary for good surface softness. Although the recycling process reduces fiber bonding ability, recycled fibers have been previously refined and they have higher bonding ability than unrefined hardwoods, resulting in reduced bulk softness (McKinney 1995).

However, the differences between recycled and virgin fibers can also be advantageous for tissue products. Recycled fibers have lower swellability and are stiffer and more dimensionally stable, resulting in a paper with higher bulk and absorbency (McKinney 1995; Hubbe *et al.* 2007). Recycled fibers can potentially be used to decrease the inter-fiber bonding (Muller and Teufel 1973). It is important to understand that different types of recycled fibers will be suited for applications where they perform well and are more economical (Hubbe *et al.* 2007).

Tissue layering and multiple plies are alternatives to maximize the performance of tissue products containing recycled fibers. For example, the use of multilayer headboxes allows the application of recycled fibers at the inner side of the ply. On the same direction, three-ply tissue can have recycled fibers in the center to give strength and virgin fibers in the outer plies to give softness (Grivas 1992). In the case of products manufactured with 100% recycled fibers, improved performance can be achieved using advanced technology (*e.g* TAD), embossing, and additives (McKinney 1995).

Mechanical and Chemical Pulps

Cellulosic pulps can also be obtained by chemical (*e.g.* kraft, sulfite) and mechanical processes (*e.g.* thermomechanical) or a combination of both methods. Mechanical pulping, especially when carried out at higher temperatures, usually separates fibers at the lignin-rich middle lamella. As a consequence, the external surfaces of mechanical fibers tend to be rich in lignin, which is somewhat hydrophobic. By contrast, removal of lignin and extractives during chemical pulping and bleaching results in fiber surfaces that are rich in carbohydrates and capable of forming stronger inter-fiber hydrogen bonding. Mechanical pulping also tends to separate fibers into a wide range of sizes due to partial breakage of tracheids and fibers, which tends to increase the content of fine particles. On the other hand, chemical pulping tends to leave the fibers relatively intact. Porosity is also different between chemical and mechanical fibers. Mechanical fibers usually have pores larger than 1 nm, while never-dried chemical fibers have pore sizes in the range of 2 nm to 100 nm due to the selective removal of lignin domains during pulping and bleaching (Hubbe *et al*. 2007). As a result of those differences, chemical pulps are more flexible and conformable; more readily flatten into ribbon-like fibers that tend to form stronger inter-fiber bonding. Chemical pulps can also be bleached to higher brightness. On the other hand, mechanical pulps are bulker, stiffer and less conformable; the lumen structure tends to be more resistant to the papermaking process (Johnsson 1978; Hubbe *et al*. 2007). Increase in tissue bulk is expected when mechanical pulps are used to replace northern pulps, such as birch and pine. However, increase in bulk will be negligible if mechanical pulp is used to replace BEK (Norwegian Pulp and Paper Research Institue 1983).

Chemical pulps tend to be more expensive than mechanical pulps because of the pulping yield. The pulping yield of chemical pulps is around 45% to 55%, while mechanical pulps can have pulping yields as high as 98% (Johnsson 1978; Norwegian Pulp and Paper Research Institue 1983; Yuan *et al.* 2016).

Mechanical pulps are much less susceptible to changes during drying and recycling. On the other hand, chemical pulps are more susceptible to those changes, especially when they are bleached and refined. The opening of voids within the cell wall, by removal of lignin and application of mechanical refining, make the cellulosic fibers more susceptible to changes during drying process, which causes a reduction of strength. On the other hand, recycling of mechanical fibers can increase their flattening tendency which may result in denser and stronger paper (Jang *et al.* 1995; Hubbe *et al*. 2007).

As a result of the mechanical action, mechanical pulps have higher content of fines and lower freeness than chemical pulps (Johnsson 1978). The high content of fine particles present in mechanical pulps affects the final properties of tissue products. Higher content of fines typically improves the strength of tissue. On the other hand, fine particles that are present in mechanical pulps or created during the refining process can significantly decrease absorbency rate of tissue paper made with CTMP and 60% northern softwood kraft. The decrease in absorbency rate can be even higher when the effect of fine particles is combined with dissolved organics, such as extractives and lignin, due to its hydrophobic behavior. This can be a problem, especially for tissue mills operating with high content of recycled water. On the other hand, fines improves dry and wet strength due to better inter-fiber bonding and better formation, while dissolved organics have a negative effect on strength (Springer and Pires 1988). Redistribution of wood components is also an important factor when mechanical and unbleached fibers are recycled. Those fibers have a higher content of wood resins that may cause self-sizing when redistributed in the fibers during recycling, resulting in increased resistance to wetting and strength reduction. However, surfactants can be used to overcome self-sizing effect. Additionally, deinking operations and successive recycling cycles will tend to decrease the extractives content of recycled fibers (Hubbe *et al.* 2007).

IMPORTANCE OF MECHANICAL REFINING

Mechanical refining is an important step to prepare fiber for papermaking. The goal of mechanical refining is to apply compression and shearing forces so that fibers will develop the required conformability, bonding capability, and tendency to form bulky or compact paper structures. On a typical refiner, the fiber stock passes between a rotor and a stator, causing fibrillation at the fiber surface and detachment of fines. Additionally, refining also promotes delamination within the cell wall which increases the wet-flexibility of fibers. The refining action also opens submicroscopic spaces within the cell wall and increases swelling and flexibility (Hubbe *et al.* 2007). As a result of the physical modifications, refining will improve bonding ability and conformability of fibers, which will result in a denser and stronger paper product. However, refining has to be used with caution during the manufacturing of tissue paper. Tissue products usually require relatively low levels of strength that can be achieved with moderate mechanical refining. The energy input in tissue refiners is normally lower than in conventional papermaking. Low refining energy not only contributes to the production of a bulkier, softer (Kullander 2012), and more absorbent paper structure but also avoids excessive reduction of water drainage rate and paper machine speed due to the increased fiber capacity to hold water. Typically freeness values for tissue machines are about 500 mL (Canadian Standard Freeness) (Watson and Janssen 2014).

Besides the total amount of energy used during refining, the refining intensity is another important variable. Refining intensity or specific edge load is a function of the design of the refining plates and can be defined as how hard the fibers are hit during the refining process. Coarse refining plates give higher specific edge load. Refining can also be performed at low consistencies or high consistencies. Low consistency refining is the most common refining option used for tissue manufacturing. However, the interest for high consistency refining is increasing. During the high consistency refining, fibers experience less interaction with the surfaces of the refiners when compared to low consistency refining (Peters 2016; Zou 2017b). The target for tissue products would be to achieve the desired strength applying minimum refining energy without compromising softness and absorbency (Gigac and Fišerová 2008).

Another important aspect of mechanical refining is how different pulp types and fiber species respond to refining action. It can be seen from Fig. 11 that there are significant differences in freeness and refining requirements among different types of market pulps. For example, for the same CSF (Canadian standard freeness), NBSK pulps yield stronger paper web than SBSK pulps on average. However, refined NBSK pulps result in lower paper bulk than SBSK pulps. When hardwood pulps are refined, SBHK pulps yield stronger paper web than BEK pulps. On the other hand, SBSK pulps tend to form a denser paper web than BEK pulps. A comparison between softwood and hardwood pulps shows that, although hardwood pulps are not as strong as NBSK pulps, their strength can approach the strength of SBSK pulps and weak NBSK pulps. Therefore, paper properties can be adjusted with proper combination and refining of hardwood and softwood pulps (Nanko *et al.* 2005).

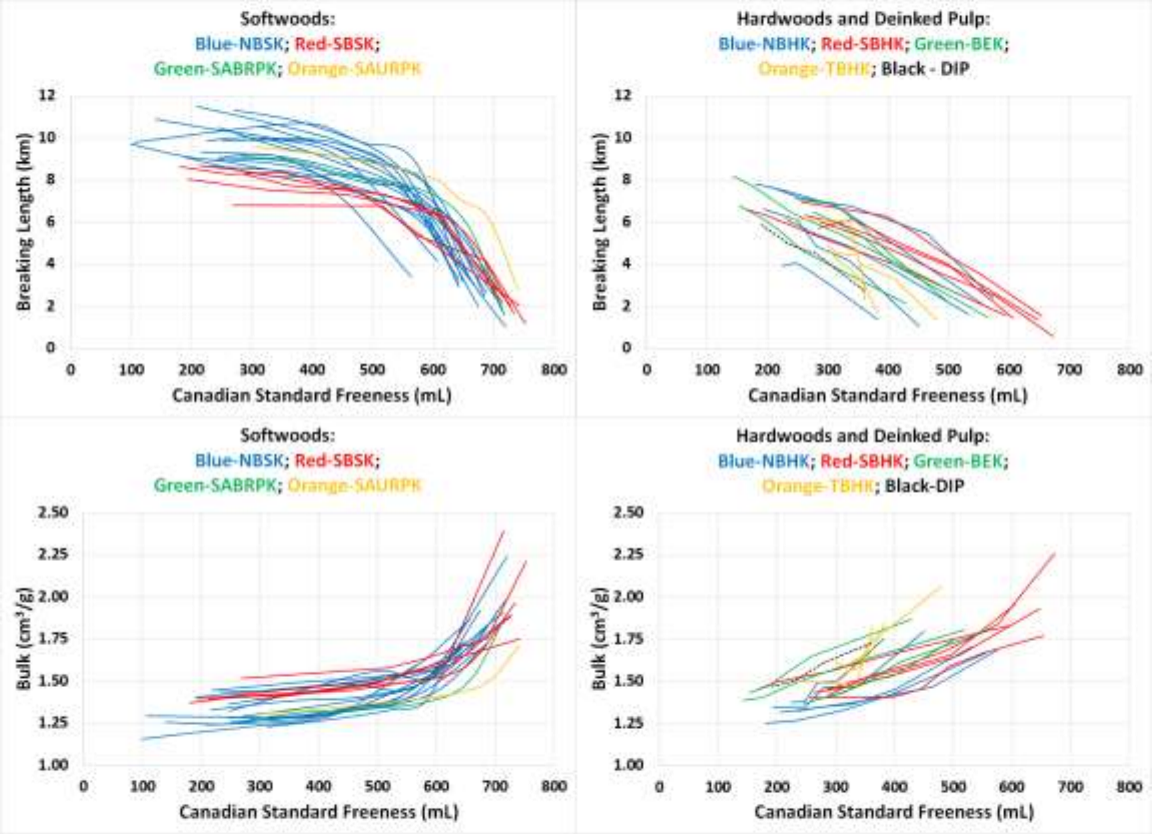


Fig. 11. Breaking length and bulk, as a function of freeness. NBSK: northern bleached softwood kraft; SBSK: southern bleached softwood kraft; SABRPK: South American bleached radiata pine kraft; SAURPK: South American unbleached radiata pine kraft; NBHK: northern bleached hardwood kraft; SBHK: southern bleached hardwood kraft; BEK: bleached eucalyptus kraft; TBHK = tropical bleached hardwood kraft; DIP: deinked pulp (Adapted from Nanko *et al.* 2005)

Effect of Mechanical Refining on Tissue Properties

Water absorbency, softness, and strength can be defined as the most important properties for tissue products. As discussed before, those desired properties are a function of technology, fibers, chemical additives, and mechanical treatment used during the tissue making process. Refining is a very common mechanical method used to modify the characteristics of fibers and achieve the desired properties of paper products.

Kullander *et al.* (2012) and Gigac and Fišerová (2008) evaluated the impact of refining on strength, water absorption capacity and bulk softness (measured as flexural rigidity) of bleached kraft softwoods (spruce, pine), bleached kraft hardwoods (birch, eucalyptus), and bleached sulfite spruce. Refining results in fibrillation and fiber straightening, which increases flexibility, bonding ability and bonding area of fibers, resulting in stronger and denser paper webs. Refining significantly reduced the weighted fiber length of spruce sulfite. No significant fiber shortening was observed for kraft fibers because kraft fibers tend to be stronger than sulfite fibers.

A comparison between wood types shows that kraft hardwoods presented similar or better dry and wet tensile indexes than kraft softwoods at the low refining levels (< 1000 PFI revolutions), which may seem to be unexpected. However, fiber length is not the only morphological aspect impacting tensile index. The increasing number of fibers in hardwood can compensate for the shorter fiber length. On the other hand, based on the same dewatering resistance, kraft softwoods presented higher dry and wet tensile indexes. Kraft spruce and pine presented the best tensile index, followed by birch and eucalyptus. Sulfite spruce showed the lowest tensile index. The advantage of softwood fibers on tensile strength diminishes as the grammage decreases, probably due to structural differences at low grammage. Additionally, the probability of encountering a weak spot in softwood sheets is higher due to the presence of a more open or porous fiber web. The relative bonded area might also be higher in hardwoods sheets due to better fiber coverage (Kullander *et al.* 2012; Gigac and Fišerová 2008).

Unbeaten softwoods presented higher water absorption capacity. Eucalyptus showed the lowest absorption capacity due to the more closed porous structure among all unrefined samples. Water absorption decreased for all pulps evaluated within the refining range of 20° to 45° SR due to the lower content of air spaces between fibers. Hardwoods (birch and eucalyptus) presented better absorption than spruce at same dewatering resistance. Spruce kraft showed better water absorption than spruce sulfite. It is usually observed that kraft pulps have better water absorption than sulfite pulps (Kullander *et al.* 2012; Gigac and Fišerová 2008).

The response of refining on bulk softness depends on many factors, such as wood type, fiber species, and the types of pulping and bleaching. Overall, hardwood pulps presented similar or better bulk softness than softwood pulps. Among the hardwoods, TCF bleached birch kraft exhibited better bulk softness than ECF bleached eucalyptus kraft. Refining increased birch softness in the refining range evaluated (20° to 45° SR), however bulk softness for eucalyptus and spruce decreased at low refining degree (less than 25° SR), followed by an increase at higher refining degree (25° to 45° SR). Sulfite spruce presented better bulk softness than kraft spruce due to a higher flexibility of sulfite pulps. TCF bleached kraft spruce kraft presented better bulk softness than ECF. However, no significant differences in bulk softness were observed between TCF and ECF bleached spruce sulfite (Gigac and Fišerová 2008; Kullander *et al.* 2012).

Refining consistency was studied at laboratory and mill scale by Wang and Chen (2015). Non-wood and wood fibers were refined at low (1.6% to 4.3%) and high (18% to 30%) consistency. Because of the lower number of shearing and compressive interactions experienced between fibers and refining plates, high consistency refining reduces fiber cutting and fines production, yielding more fiber deformations (curl and kink). High consistency refining resulted in same bulk, better strength (tear and tensile), and lower refining energy consumption when compared to low consistency refining at same freeness level.

Mechanical refining of non-woods (bagasse, wheat straw and rice straw) has also been studied. Very light refining has shown to increase the number of fines for the whole non-wood pulps due to loosening of parenchyma cells aggregates. Fines content also increased when only longer fiber fractions (fibers retained at 200 mesh and 50 mesh screening) of the pulps were refined. However, the source of the fines depends on the type and strength of the fibers. External fibrillation has caused an increase in fines content in the case of bagasse and wheat straw fibers, while fiber shortening was the main source of fines production during the refining of rice straw fibers. The removal of non-fibrous fines yielded a stronger sheet at a given freeness (Roy *et al*. 1994). The level of energy applied during the refining of non-wood fibers is also an important variable. The use of high specific edge loads during the refining of wheat straw and bamboo caused the disaggregation and disintegration of parenchyma cells, resulting in rapid decrease of drainage and denser paper web. Parenchyma cells have thin cell wall that can be more easily disintegrated than fibers under mechanical action. On the other hand, refining at lower specific edge loads shown better bulk and strength due to better preservation of the physical integrity of fibers (Subrahmanyam *et al*. 2000).

The effect of refining intensity on wood pulps for tissue making has also been studied. However, the results are contradictory. Zou (2017b) showed that low specific edge load gives better tensile strength and bulk at a given refining energy or drainage for NBSK pulp. On the other hand, Gigac and Fišerová (2008) showed that higher specific edge load improves bulk softness and absorbency for different bleached hardwood and softwood kraft pulps.

Trepanier (2017) has discussed the impact of refining energy on fiber length and curl (fiber curvature) and kink (abrupt change in fiber curvature). The use of low energy (60 kWh/o.d. metric ton of pulp) during low consistency refining does not change the fiber length, but it significantly reduces fiber curl and kink, which increases tissue paper density. Subsequent increase of refining energy does not change fiber curl and kink significantly, but a reduction of fiber length is observed.

FINAL CONSIDERATIONS

Although there is a vast number of publications evaluating the use of different fibers on writing, printing and packaging paper grades, fewer peer-review works have been published dealing with tissue manufacturing. As noticed by other authors (*e.g.* Hall 1983), the lack of scientific research on tissue paper is probably a result of high competition and secrecy among different tissue producers and suppliers. There is a lot of opportunity to explore the effect of fibers, especially non-wood fibers, chemical additives, and process alternatives on tissue properties. Additionally, there is a need for standard procedures to make and test tissue products. Several works on tissue products use pressing to form handsheets at laboratory scale. Pressed handsheets will present much higher apparent density than the usual values found in tissue products (from 150 kg/m^3 to 350 kg/m^3), resulting in poor absorbency and softness. In order to better mimic the tissue making process, standard handsheets can be lightly pressed or not pressed at all. As discussed before, density is a very important property for tissue products and can be considered as the major difference between tissue and other paper grades.

SUMMARY STATEMENTS

1. Machine technology and fiber type significantly affect the final properties of tissue products. Conventional technology, such as dry-crepe, uses pressing to partially dewater the paper web, which promotes the reduction of bulk resulting in poor softness

and absorbency. Advanced technologies, such as Through-Air Drying (TAD), produce tissue products with high bulk, softness, and absorbency.

2. Different types of fibers and pulping process contribute to different aspects of tissue products (Table 6). Softwoods are mainly used as a source of reinforcement, while hardwoods provide softness. Non-wood biomass has a wide range of fiber morphology with properties similar to hardwoods and softwoods, depending on the species. Mechanical pulps have stiff fibers and can be used to create a bulkier paper web. Chemical pulps are flexible and conformable, resulting in better bonding ability combined with better softness. Virgin fibers are more flexible and produce stronger and softer tissue products. On the other hand, recycled fibers are stiffer with lower bonding ability and have higher content of short fibers and fines, yielding tissue products that are weaker and less soft.

Table 6. Properties of Fibers Used in Tissue Products

Fiber	Strength	Softness	Water Absorbency	Bulk
Hardwood	+	+++	++	+
Softwood	+++	++	++	+
Non-wood	+	++	++	++

Pulping Process	Strength	Softness	Water Absorbency	Bulk
Chemical	+++	+++	+++	++
Mechanical	+	+	+++	+++
Recycled	++	+	+	+

3. Mechanical refining is commonly used to improve the limitations found in recycled fibers and to develop desired properties in virgin fibers. At the same time that refining increases tissue strength, it also decreases bulk and water absorbency.

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