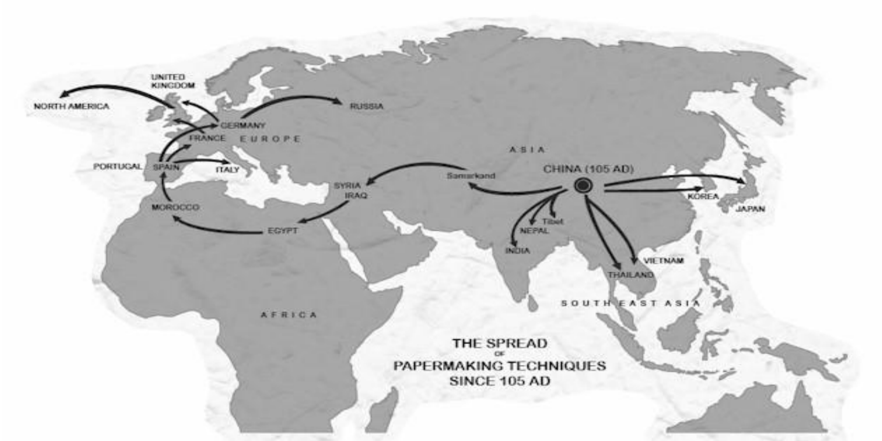
IT'S NOT TAPE WITHOUT A SUBSTRATE – OR HOW TO MAKE PAPER 101

Cheryl B. Rueckert, Ph. D.
Senior Research Fellow
Neenah Paper, Inc.
Munising, MI

Background

The development of paper has been considered one of the keystone events in human civilization due to its ability to easily prepare, record, and store information (compare it to clay tablets, leaves, or animal skins). In its most ancient current form, paper has been credited to be developed in China at 105 AD. What differentiated the Chinese form to be 'paper' from papyrus (reeds pounded together until they formed a single layer) was developing 1) a process to separate the fibers prior to 2) forming the sheet onto a sieve-like screen before drying. From this time until the18th century, paper spread around the world but it was still made one sheet at a time. Paper fiber was originally from grasses, hemp, bamboo, sugar cane, and cotton to name a few. It wasn't until after the production of paper spread around the world and shortages of the preferred fibers happened that developers experimented with wood as a source of fiber in the latter half of the 1800's.[1]



The westward migration of Chinese papermaking techniques.
(Graphic Design by Anchalee Wannasupring)

Figure 1.[1]

Why is the type of tree important in paper making?

Fiber morphology is the short answer. A wood fiber, or tracheid, is shaped like a straw with an outer wall and a central open core (lumen). The outer wall is made up of many different layers of smaller fibrils consisting of cellulose, hemicellulose, and lignin (a class of complex organic polymers that form important structural materials in the support tissues of vascular plants) with each layer having different fibril orientations along the length of the fiber for strength (a bit like a girdle) in a lightweight package.

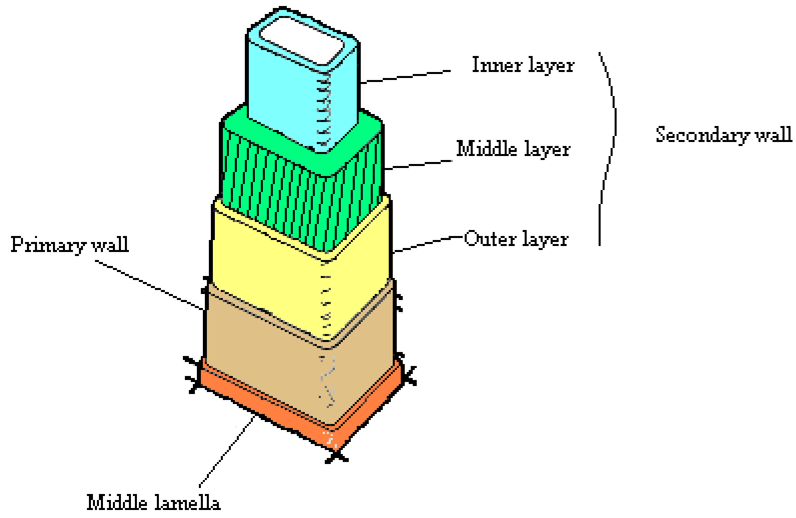


Figure 2. Schematic of the internal structure of a tree fiber.

Trees are generally grouped into two segments depending upon whether they keep their leaves throughout the year. Those that do are called Evergreens (or softwoods) and those that drop their leaves at the start of winter are called Deciduous (or hardwoods). Softwoods have longer paper making fibers than hardwood fibers (approximately 2X when measured in a wood chip), have thicker cell walls, and a larger diameter lumen. The softwood and hardwood nomenclature is derived from those using the wood (think carpenters) as hardwood is generally much harder and denser (less likely to dent when struck) compared to softwoods (but there are exceptions).

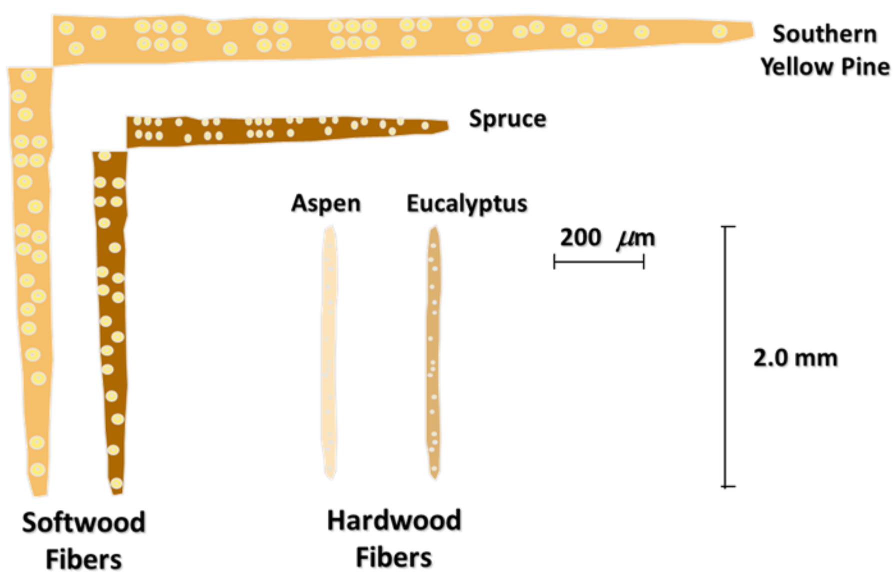


Figure 3. Examples of differing fiber morphologies between fiber species and types.

Given the same number of fibers, a pile (or sheet) of softwood fibers will be bulkier, rougher, and coarser (a property that compares fiber weight per length). That bulkiness will allow more air through the sheet (a more open porosity) and the longer fiber length is a critical factor to developing higher tear strength. Hardwood fibers excel in papers where smoothness, lower bulk, better formation, lower porosity, and higher tensile strength is desired. Papers that are made with blends of hardwood and softwood fibers can generally balance to achieve the needed properties. With proper fiber preparation before paper making, some of the differences between the fiber types can be mitigated.

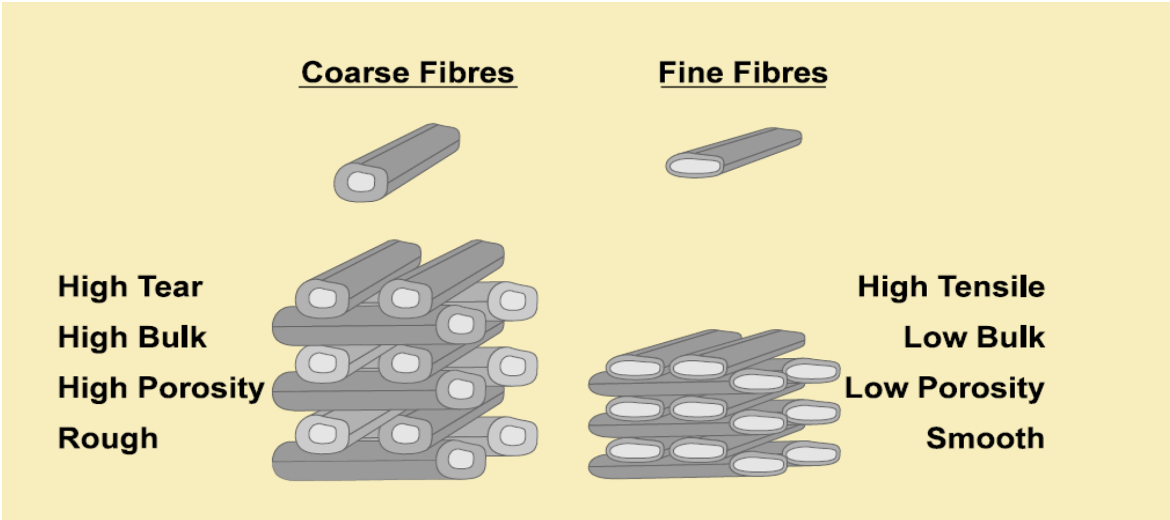


Figure 4. How different fiber morphologies make different properties of paper.

How to make trees into pulp

The trees that are used to make wood pulp are generally harvested from farms or managed forests. These trees will go through a board producing factory (sawmill) and the pulp fiber would be the by-product. In the U.S., the total forested area is now equal to the level of 100 years ago and grew by 2 million acres from 2000 to 2005. Today, the United States has 20 percent more trees than it did on the first Earth Day celebration more than 40 years ago.[2] After harvesting, the trees are trucked to a facility to remove the bark and outer debris before further processing into boards/veneer with remainder being made into wood chips.

At this point decisions are made about how the pulp will be produced. There are two general methods of producing pulp from wood – mechanical or chemical. If the chips are to be made into mechanical pulp, the most common method is to send the chips through large refiners that shear and cyclically compress the chips with tighter tolerances and higher frequencies as they pass through the refiner. At some point within the refiner, the chip separates into individual fibers and wood fragments. Mechanical pulping generally has a very high yield as almost all of the chip is turned into usable pulp. This is a very energy intensive process and most mechanical production has added some chemical pretreatment to soften the chips prior to refining. This pulp still retains the lignin in the fibers and due to this, the fibers can't be as fully bleached as a chemically produced pulp and the fibers will show color reversion (they become darker/yellower) when exposed to UV light or temperature. The paper generally produced from this pulp is bulky with very good opacity but lower strength and a tendency to retain water during the paper making process.

With the chemical process the wood chips are loaded into a digester (which is similar to a pressure cooker) along with water and chemicals (generally sodium hydroxide and sodium sulfide as the active agents in the Kraft process). The conglomerate is pressurized and heated to soften and help solubilize the lignin that provides rigidity and hydrophobicity in a tree. The fibers are now separated but still retain quite a bit of lignin, which is darkly colored, but can be made into paper at this time if the color is not an issue (bags and boxes commonly use brown fiber). The majority of the fiber is bleached in various multistage processes (using peroxides and chloride dioxides) to further remove lignin but leave as much chemically undamaged cellulose as possible (one of the benefits of moving away from the stronger elemental chlorine bleach). Chemical pulping is a lower yield process (around 50% of the chip mass is lost to by-products) but can yield a very strong white pulp that has multiple uses.

Paper making

Stock preparation

Prior to making the fibers into a sheet of paper, the fibers go through many processes to achieve the desired end properties in the paper. The main process is refining the fibers to achieve the strength or porosity needed. Fibers can be thought of as smooth tubes and as such they don't mechanically intertwine and hold onto other fibers or flatten into a smooth sheet without mechanical energy being applied through refining. The shear and cyclical compressions of refining cause the fiber to fibrillate on the surface and in the cell wall. This causes the overall fiber structure to loose stiffness and allows the central lumen space to collapse making a much denser sheet. Taking refining to the extreme generates glassine paper (the translucent paper used to make 'windows' in envelopes). As fibrils are generated and the lumen collapses, a larger area between the fibers are now in contact to generate greater fiber entanglement plus the larger contact area leads to greater hydrogen bonding between the cellulose fibers once dried. The collapsing of the fibers will also cause the sheet porosity to greatly change. Just a little refining will make a sheet that air can penetrate easily while a well refined sheet blocks the air and makes a more torturous path through the sheet – a much higher porosity.

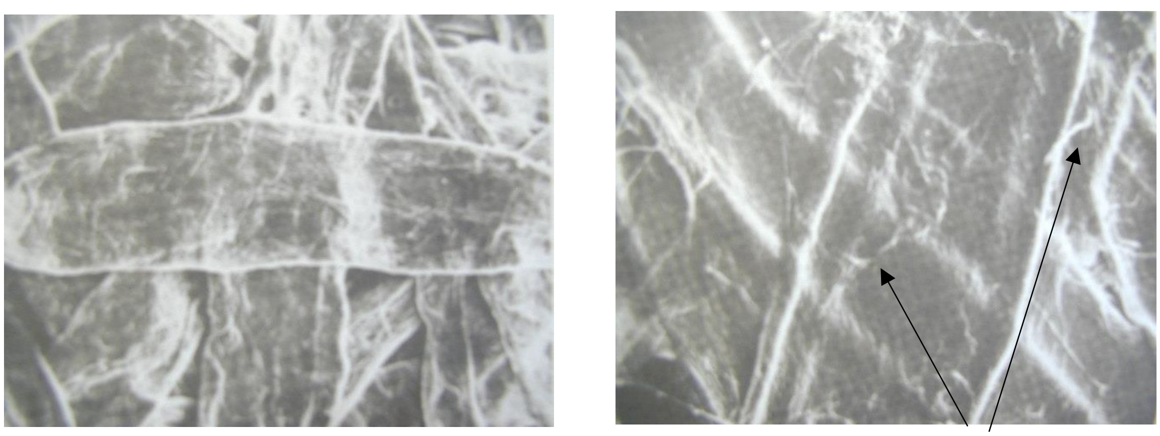


Figure 5. SEM images of paper fiber before and after refining (fibrils)

In addition to refining, there are other mechanical process that will generall be required prior to the pulp being made into paper. On the way to the paper machine, but after refining, the fibers are screened to eliminate any oversized material being allowed into the sheet. There are also hydrocyclones that filter the pulp slurry (fiber and water) by density – these can clean either heavy or lighter density matter from the acceptable fiber stream.

Chemical additives are also added to the pulp slurry to help create the desired sheet. A main additive is colorants (very important for most papers). Colorants may be either dyes or pigments. Dyes are easier to add in the wet stock but require other additives to adhere them to the fiber but have duller color and generally poor UV resistance but this differs by color. Pigment colorants require chemicals to trap them into the sheet web and give a more vivid color and generally good UV resistance but can be more costly. Other additives could be wet strength resins, dry strength resins, or sizing agents (for hyrdophobicity).

The Fourdrinier paper machine

Until the invention of the Fourdrinier paper machine, every sheet of paper was produced one sheet at a time. The Fourdrinier brothers funded the production of the first patented continuous paper machine in the very early 1800's. There are four basic sections of this paper machine – a wet end, wet press, dryer, and calender sections. The pulp slurry that has been previously prepared has now been diluted with water down to a consistency of approximately 0.5% (meaning that there is 0.5 kg of dry pulp in every 100 kg of wet slurry) that is pumped into the headbox. The headbox is pressurized and sprays the fiber slurry out of a narrow slot called the slice lip onto a moving polyester screen. In the early days of paper making this was a wire screen, and terminology today still describes the polyester mesh screen as a 'wire'. The purpose of the wire was drainage of a large portion of the water through the least expensive methods possible (of which the first is gravity, followed by passive Bernoulli type pressure pulses, and then vacuum systems). At the end of the wire, the consistency of the sheet is now 20%, or 97.5 kg of the original 99.5 kg of water have been removed from the 0.5 kg of dry fiber. Traditional Fourdrinier paper machines have a horizontal surface that the fiber slurry rides along, while more modern machines have changed the orientation or added a second wire. The side of the paper sheet that touches the polyester 'wire' is called the wire side of the sheet to paper makers.

The wet press section of the paper machine can contain between one to three presses. The wet sheet is threaded through 2 rolls under pressure and the water is literally squeezed out of the paper. Also threaded through the presses is a felt (a thick strong absorbant fabric) that captures the water pressed out of the sheet. The felt travels through the nip of the two rolls and then around to a dryer to remove the majority of the water before returning to the nip to absorb more water. The felt generally touches the topside of the sheet and is considered the opposite side of the sheet from the wire side, even if the felt is on the wire side.

After the sheet leaves the wet press section, the paper now enters the dryer section. This is a series of steam heated pressurized vessels that rotate with the damp sheet threaded around them in a serpentine fashion. The sheet is held to the dryer can surface by a different type of felt (made from a breathable material to allow the steam produced from the heated sheet to pass through it).

The last section in the traditional Fourdrinier is the calender section. The sheet leaves the dryer cans and passes through a series of nipped rolls (generally presented in a stacked method to save floor space) where the sheet is compressed and the byproduct is a thinner, denser, and smoother paper.

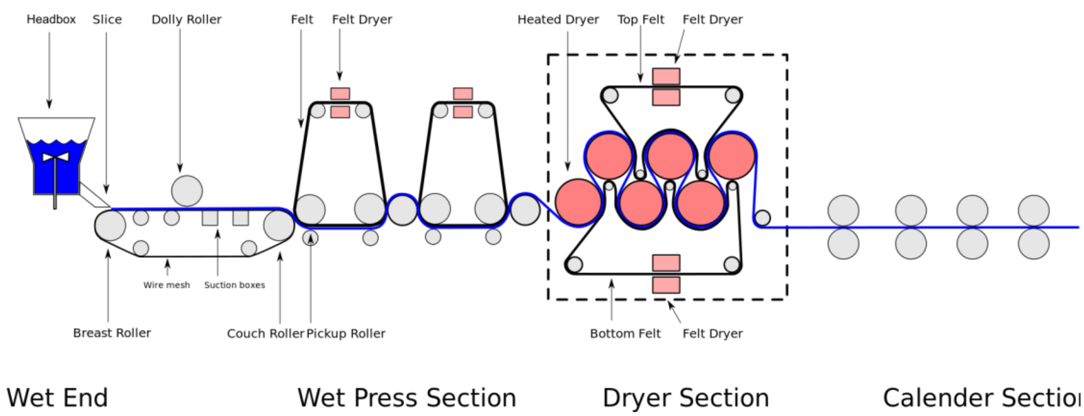


Figure 6. The layout of a traditional Fourdrinier paper machine[3]

Paper machines are large pieces of equipment. They range from being able to make paper 60" wide up to the current largest machine at 465" wide and nearly 2000' long. Some machines will run as slow as 50 feet per minute but the fastest has run at 2100 meters per minute (which is 78.3 miles per hour)! Estimating the price tag on a new small paper machine (on an existing site), one would expect to pay approximately $80 million and the price rapidly escalates if this is a greenfield site, if you are planning to run an intregrated mill (meaning adding a pulp mill also), and is very dependent on the size and complexity of the desired machine.

Fiber Orientation

Paper makers refer to a sheet of paper in many ways. I have already presented the ideas of wire and felt side of the sheet, but there is also MD, CD, and ZD orientation. These acronyms stand for machine direction, cross direction, and the direction perpendicular to the horizontal surface of the sheet. The machine direction of a sheet is in the direction that the sheet travels down the length of the paper machine. The pulp slurry is jetted out on the moving wire. As with canoes and kayaks in a moving stream, the slender fibers will generally align their length in the direction the water is flowing. The cross direction is the direction across the machine or the machine width.

The effect of fiber orientation is apparent in the physical properties in a sheet of paper. When you compare tearing a sheet of newsprint in the MD and CD, you will notice the MD tears generally in a straight line while the CD tear is jagged and curved. Thinking down to the fiber level in the sheet, as a tear progresses through the sheet it will find it much easier to tear along the length of the fibers (MD) than across the width of the fibers (CD).

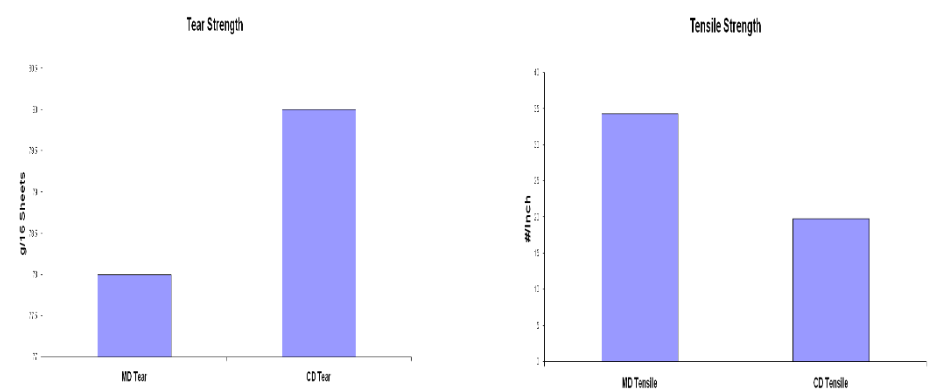


Figure 7. The impact of fiber orientation on the strength of the paper.

Flat vs. Creped paper

The sheet of paper that we have been making on our traditional Fourdrinier machine would be considered to be 'flat' to a tape producer. The majority of paper tapes are creped during the drying section of the paper machine (and sometimes just before the dryers). Creping imparts a texture to the sheet that can be almost flat (a fine crepe pattern) or very bumpy (coarse crepe). This texture is achieved through the process of running the damp (or wet) sheet over a drying can and instead of smoothly pulling it off that can and traveling to the next can, the sheet is instead bunched up when it bumps into the creping blade on the dryer can. The physical action of bunching the sheet up creates much more MD stretch in a sheet than is possible with a flat sheet (which is good for tape suppliers when the customer wants to mask a rounded surface). By controlling how fast the sheet is pulled to the next dryer can will determine how much pattern and (MD stretch) will be left in the sheet. The crepe pattern is also determined by additional factors such as sheet moisture, type of creping blade, machine speed, and adhesion of the sheet to the creping surface among others.

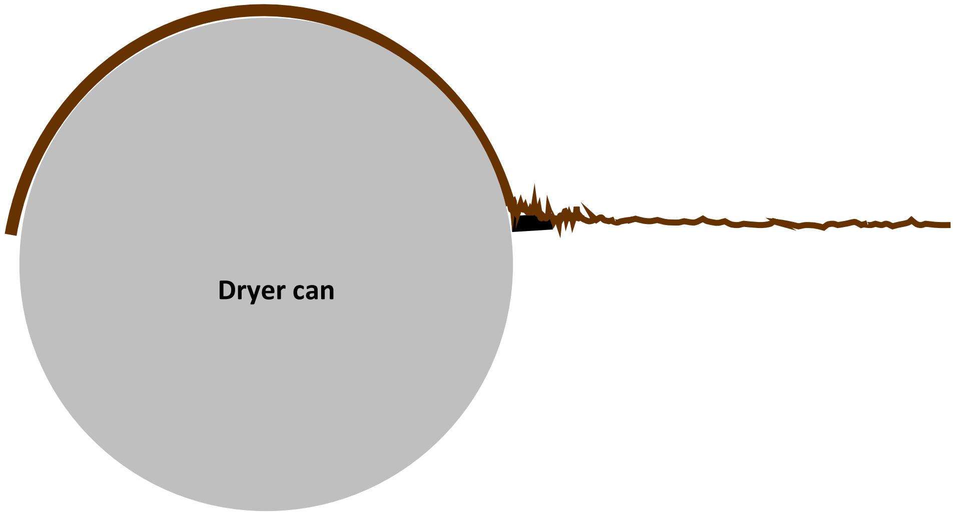


Figure 8. Sheet of paper, dryer can, and creping blade (machine direction is moving to the right).

Saturation

To this point, we've discussed how to build a strong base fiber sheet. Strength and durability, whether that is related to tensile, delamination, tear, or temperature resistance can then be enhanced by impregnating (saturating) the internal structure of the sheet with natural or synthetic polymers and other chemicals. As with the paper sheet, balancing properties is key when determining the mix of chemicals used in the saturants. It is important to note that delamination problems can occur with paper when complete penetration of the polymer into the paper is not achieved. Saturation is a good method to improve the holdout of any potential coatings that could be applied to the paper sheet. Further drying is required after the saturation step and can occur in a constrained (felted) or non-constrained (floatation) dryer section.

There are many different ways of changing the sheet properties during saturation. Depending upon the Tg, or glass transition temperature (the hardness) of the latex, the sheet will change its strength properties and also the stiffness. Adding a higher percentage of latex saturant to the sheet will increase physical properties but there are diminishing returns after a point (which will differ with each type of paper and latex). Colorants and other additives can also be added to the saturant to enhance the desired end property.

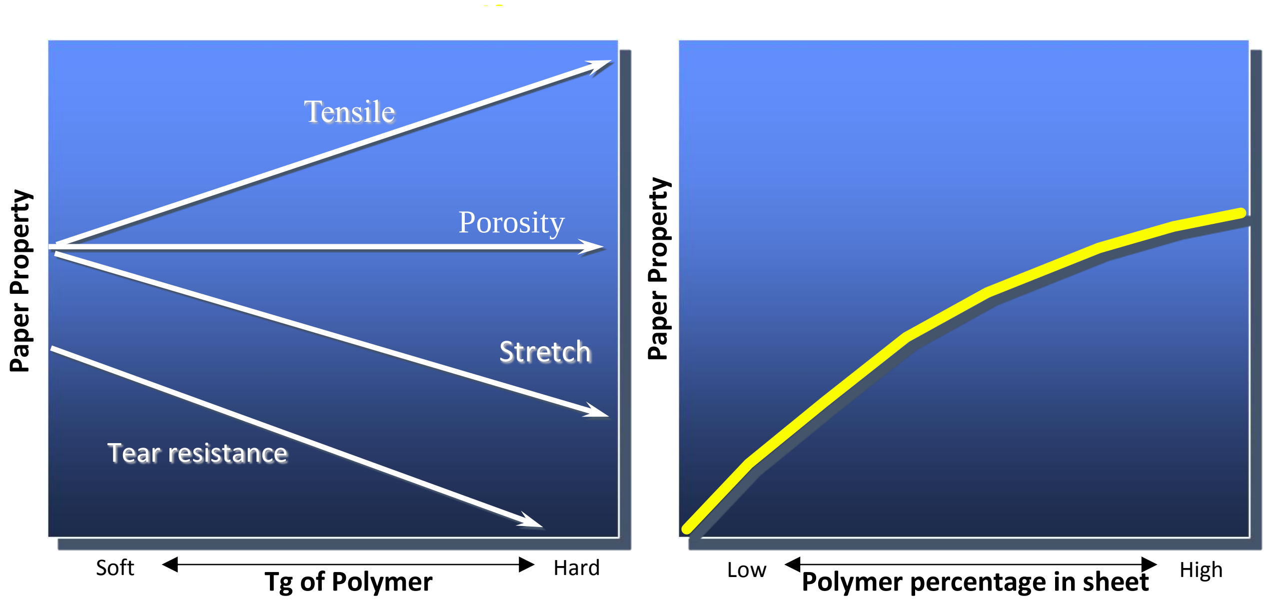


Figure 9. How latex saturation can change the physical properties of paper.

Coating

Papers used for manufacturing tape products generally require a release treatment on one surface and often times benefit by a "tie-coating" which can improve the anchorage of the pressure-sensitive adhesive on the other side of the paper. These coatings can be applied on the paper machine or on a separate, precision coater. The materials used in these treatments are often proprietary to the paper manufacturer and will vary depending upon the degree of release desired for the product and the composition of the adhesive applied by the converter.

Conclusion

Paper manufacturers have many levers that can be pulled to produce the performance that is needed for your tape application. From choice of fiber type and amount of latex, and type and amount of coatings – custom products are a way of life for the specialty paper company.

Literature Citations

1. https://www.poopoopaper.com/en/content/11-history-of-paper
2. http://www.afandpa.org/our-industry/fun-facts
3. https://en.wikipedia.org/wiki/Paper_machine

Acknowledgments

Thank you Joe Terry and Jay Baxter for asking me to submit an abstract for PSTC. I would like to thank the Munising group of R&D scientists for helping to edit and proof this document and presentation.