Effects of forming fabric structural parameters on sheet properties

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ABSTRACT: Forming fabric structures and critical properties that affect papermaking process and paper properties are discussed. The relationships between certain forming fabric parameters and paper properties are examined experimentally. The design of the forming fabric affects basic sheet properties such as integrity, strength, and thickness. Variations in fabric properties due to design change cause differences in sheet properties and papermaking process. Experimental data were used to investigate the effects of forming fabric characteristics, such as air permeability, drainage capacity, fiber support, thickness, density, plane difference on basic physical properties of paper, i.e., tensile, burst, and tear strengths, uniformity, and thickness. It was determined that definite relationships exist between fabric and sheet properties. These relationships are discussed.

KEYWORDS: Bibliographies, design, forming fabrics, mechanical properties, paper properties, parameters, physical properties.

Paper machine clothing is one of the most important elements in papermaking. Among the three types of paper machine clothing, forming fabrics are probably the most critical to design. They affect the final sheet properties more than press or dryer fabrics. If the sheet structure is not formed properly in the forming section, it hardly would be possible to correct it later on in the paper machine. Therefore, forming fabric design requires careful attention and a high level of engineering. Establishing the correct relationship between the forming fabric design and paper properties is the purpose of the research work being conducted at Auburn University.

Forming fabrics are used as the support, drainage, and transportation means in papermaking *(1)*. Sheet formation is not a positively controlled process. Once the fibers leave the headbox, there is not much that can be done to control individual fibers directly. According to Kufferath *(2)*, retention of fibers follows a course of chance and therefore, mathematically, it is a statistical process. He suggested that retention of fibers on a fabric follows an exponential function. There are three types of hydrodynamic processes during formation: drainage, oriented shear, and turbulence *(1)*. By controlling drainage, the orientation of fibers in the vertical direction could be controlled to some extent. Too slow drainage results in poor formation. Oriented shear is the result of the difference between fabric speed and headbox exit speed. Turbulence is needed to prevent flocculation before the fibers hit the forming fabric to achieve uniformity and good formation of the sheet. These three mechanical processes play extremely important roles in sheet formation and are investigated rather extensively *(3–12)*. However, there is hardly any publication that examines the relation between forming fabric parameters and paper properties. The effects of structure and properties of forming fabrics on papermaking and paper properties are the subject of this work.

Due to the dynamic and complex nature of the papermaking process, conducting experimental work on

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paper machines is too costly and not practical. To simulate the formation process, most of the time, handsheet formers are used in laboratories. Although an exact simulation of a dynamic process is not possible under semi-static conditions in the laboratory, some of the important conditions can be controlled to get meaningful results of interest.

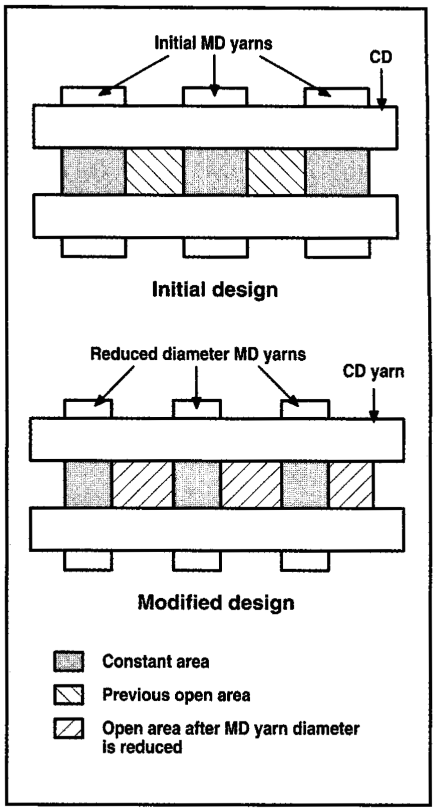
The primary objective of this research is to establish a relationship, through experimentation, of forming fabric characteristics to the properties demonstrated in the sheet of paper. Several fabric samples representing a range of designs and properties were used to make handsheets. The resulting paper samples were tested according to TAPPI Methods.

Fabric design parameters that affect paper properties

Some properties of forming fabrics have significant effects on paper structure. These properties are also crucial to the fabric's successful performance on the paper machine. Air permeability, fabric density, modulus, fiber support index *(13)*, drainage index *(14)*, caliper, cover factor, percent open area, and void volume are the most important fabric properties. The forming fabric designer can control these properties by properly selecting fabric design parameters such as yarn materials, warp and weft count, weave patterns, shed numbers, and strand diameters. These fabric properties affect many paper machine operations including drainage, formation, fiber retention, sheet release, wire mark, fabric cleaning, and fabric life.

By proper selection of yarn diameter and warp and weft count, it is possible to obtain various hole sizes and open areas to meet the machine and paper requirements. For example, by changing the MD (machine direction) yarn diameter and mesh, the percent open area can be changed without changing the hole size, as shown in **Fig. 1**. If the percent open area is adequate but more sheet support is needed, the MD yarn diameter can be reduced to give a greater number of smaller holes with the same percent open area. By proper selection of the additional number of MD yarns, the percent open area could be held constant.

1. Changing the percent open area without changing the hole size

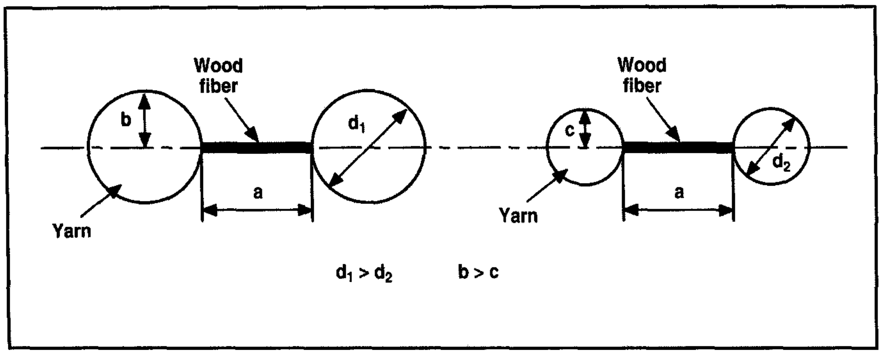


Different paper grades require different forming fabric designs. When selecting a design for a specific application, paper properties (grade, type of furnish, recycled fiber content, paper weight, wire mark, formation type) and paper machine parameters (machine type, machine length and width, speed, type of pickup, paper machine elements, operating tension) need to be considered. For example, for tissue, the current trend is to obtain soft, high bulk (less wood fiber content) product. This could be accomplished by orienting the wood fibers in the vertical direction by proper forming fabric design. Standard two-layer and two-layer extra fabrics have been successful for newsprint and fine paper applications. For tissue and brown paper, low-density two-layer fabrics were proved to be successful. Three-layer fabrics are ideal for fine papers, carbonizing, newsprint, and light specialty grades. However, three-layer fabrics cost considerably more than two-layer fabrics and the difference in cost may not be justifiable in some applications.

Forming fabric design affects sheet smoothness, retention characteristics, and sheet integrity which, in turn, affect the optical and physical properties of the sheet. Hole size and shape determine wood fiber bridging between the yarns. They also affect fiber orientation. For a given warp count, hole size can be altered by changing the number of weft yarns per unit length. In a fabric structure, the point of initial fiber bridging in the fabric is the point where a plug of fiber-filler-fines begins to form. When the fabric structure is changed by changing the yarn diameters, as shown in **Fig. 2**, the depth of initial fiber bridging is changed. The depth of the point of bridging can be decreased by using finer yarn diameters and higher mesh count while maintaining or increasing the percent open area. As a result, a plug of less total mass is formed closer to the fabric surface. The height of the hills on the fabric side of the sheet becomes less. A lower hill means more uniform calendering and a smoother sheet *(15)*. This explains why larger diameter yarns are more suitable for tissue and finer yarns are more suitable for fine paper. In Fig. 2, $d_1 > d_2$ and the fiber length a is the same in both cases, which is equal to the distance between two adjacent yarns. As can be seen from the figure, the depth of the fiber bridging is less on the right side because $c < b$.

Wire mark is the result of optical and physical characteristics of the sheet caused by density fluctuations

2. Fiber bridging for different yarn diameters



and fabric surface differences caused by fabric topography. By minimizing the plug density effect and the height of the knuckle above the fabric plane, the wire mark would be minimized. For this purpose, fabrics are surfaced to obtain monoplane surface.

Running attitudes of forming fabrics are dictated by the paper grade and fiber types. There are two fabric running attitudes: long CD (cross machine direction) knuckle up (to the sheet) and long CD knuckle down (to machine side). Running fabrics either way affects the paper properties and fabric running conditions. The effect of running attitude on fiber support (fiber bridging) is shown in **Fig. 3**. Long CD knuckle to the sheet side gives shorter distances for fibers to bridge resulting in higher fiber support (Case A). In the case of the long CD knuckle down, the proud knuckle is in the machine direction, which is the direction of water flow. Since fibers tend to orient in the flow direction, fiber bridging that is closer to top fabric surface becomes more difficult.

Experimental analysis

The selected fabrics had different structural properties. Handsheets were made using a British sheet former according to TAPPI Test Method T 205 om-88 *(16)*. The forming fabric piece was placed in the sheet former as shown in **Fig. 4**. The pulp consisted of 60% bleached hardwood and 40% bleached softwood. The pulp was disintegrated 2.5 min using a disintegrator. The resulting freeness of the pulp was 625 mL CSF. After formation, the sheets were pressed twice while on the fabric at 50 psi. The first pressing lasted 5 min, while the second pressing lasted 2 min. The sheets were then dried at room temperature. A standard amount of fiber (1 g) was used for each handsheet. The fiber lengths in the slurry ranged between 0.87 mm and 4.36 mm with an average of 2.05 mm. The maximum hole diagonal of the fabrics used was 0.79 mm, which was lower than the minimum fiber length to ensure proper fiber bridging. The basis weight of the sheets ranged from 41.24 g/m^2 to 49.92 g/m^2 with an average of 47.01 g/m^2. The fiber retention was between 82.89% and 98.95% with an average of 94.49%. No retention aid was used.

Air permeability and drainage index, fabric thickness, fiber support index, fabric density, and percent open area were used as independent variables. The dependent variables were arrived at by testing the sheets produced from each fabric. Tested sheet properties are tensile strength, burst strength, tear strength, uniformity, and thickness. Tests were done on each sheet in both the MD and CD. Paper samples were conditioned in standard environment before testing.

Tensile strength is important for many papers, such as wrapping, bag, gummed tape, cable wrapping, etc., which may be subjected to direct tensile stress. Machine direction tensile strength is especially important for printing papers such as newsprint. Tensile strength of a paper can be affected by controlling the orientation of the fibers with proper forming fabric design. Tensile strength increases along the direction of fiber orientation. The tensile strength of each paper sample was determined in each principal direction according to TAPPI Method T 494 om-88, using the Instron as a constant rate of elongation device *(17)*. This method was altered slightly by changing the gauge length to 3 in. and the rate of elongation to 0.5 in./min. Results are expressed in terms of maximum load to break the sheet sample. It should be noted that since paper is both viscoelastic and hygroscopic and has both plastic and elastic characteristics *(18)*, changing the rate of application of force in a destructive test may affect the results. Various models are available in the literature to describe the elastic, viscoelastic, and inelastic behavior of paper *(19)*.

Burst strength is used as a measure of rupture resistance in some paper types. The loading mechanism of paper in bursting is similar to tensile loading. Burst strength can be altered by forming fabric properties. The bursting strength of each paper sample was determined according to TAPPI Method T 403 om-85, using the Mullen burst strength tester *(20)*. Results are expressed in kiloPascals (kPa) required to rupture the sheet structure.

Good edge-tearing resistance is required for papers where handling is important. Edge tear strength of the handsheets was determined according to TAPPI Method T 470 om-89 *(21)*. The Instron was used as a constant rate of elongation device. The gauge length was changed to 1.5 in. and the rate of elongation was changed to 0.5 in./min. Results are reported in Newtons of force required to tear the sheet.

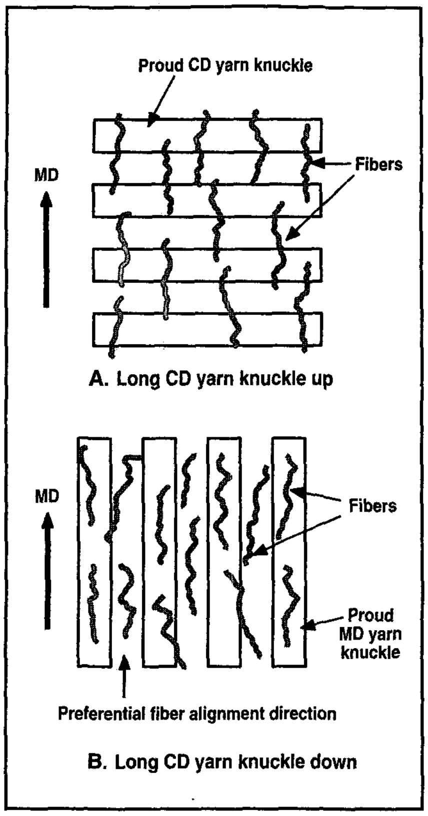
Uniformity is an indication of good formation. Sheet formation is important for pressing and drying efficiencies as well as the final paper properties. Nonuniform formation can lead to density variations. Uneven fiber distributions give uneven printing results *(22)*. Testing of sheet uniformity is not a straightforward method, and most of the time it is subjective. Uniformity of the sheets was determined by visual inspection.

Thickness is an important paper property because variations in thickness affect the use of paper and paperboard for mechanical purposes. The thickness of each sheet was determined according to TAPPI Method T 411 om-89 *(23)*. The device used was a TMI thickness tester with a 16-mm diameter pressure foot and anvil. Results are expressed in millimeters.

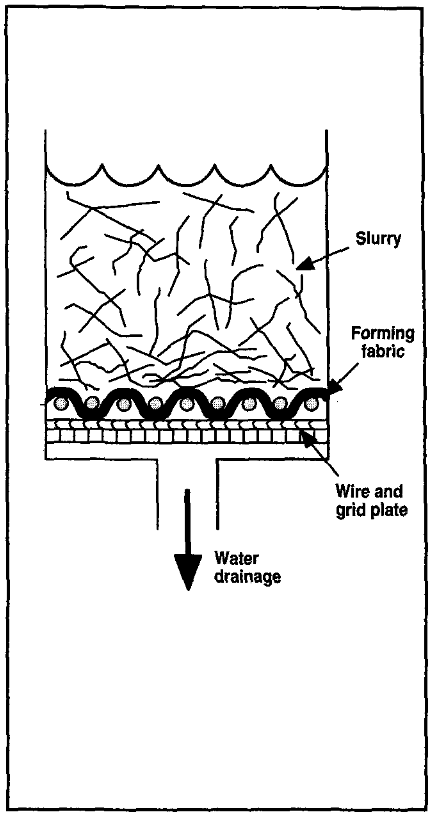
Results and discussion

The results from the experiments are given below. In the graphs, curves are fitted to experimental data points and a formula for each curve is given along with correlation coefficient. The outliers (between 1 and 3 data points) were eliminated from the data. Thus, the curves represent the empirical relationships between sheet and forming fabric properties. It should be noted that papermaking is a dynamic process in which both slurry and forming fabric run at high speeds. The resulting paper properties, largely depend not only on fabric characteristics, but also on these dynamic conditions. Therefore, it is difficult to simulate the actual running conditions of a forming section with semi-static conditions using British sheet former where drainage is by gravity and therefore fewer forces are involved. This fact should be kept in mind when analyzing the results.

3. Effect of fabric running attitude on fiber support



4. Schematic of the placement of forming fabric in the sheet former



Effect of fabric air permeability and drainage capability

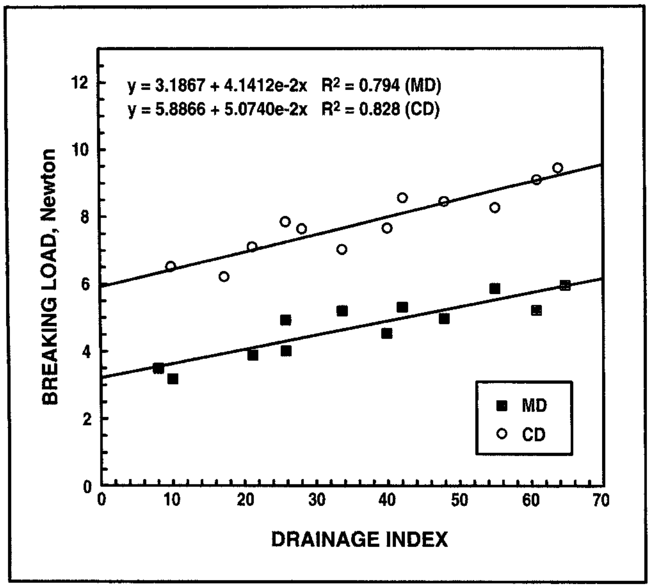
Forming fabric drainage characteristics affect paper machine performance and final sheet quality. Air permeability indicates forming fabric drainage capacity. The increase in air permeability had noticeable effects on tensile, burst, and tear strengths of the sheets as shown in **Figs. 5, 6, and 7**, respectively. As air permeability increases, the water permeability also increases. This allows for a faster rate of flow through the fabric which, in turn, imparts closer interaction between fibers in the fiber mat being formed. The more interaction that occurs, the stronger the sheet becomes. That is why sheet strengths are lower in fabrics with low drainage indices in the figures.

On a paper machine, drainage capacity is also affected by the fiber and fabric interface. Once the initial fiber mat is deposited on the fabric, it starts reducing drainage capacity of the fabric with blocking effect. Initially retained fibers act as a fabric and retain subsequent fibers. As the drainage velocity increases, sealing effect also increases; however, the retention of fines and fillers improve. As a result of decrease in drainage, paper strength also decreases which is similar to the effect shown in Figs. 5–7. In practice, high drainage is generally preferred since it would allow lower headbox consistency which is a tool to optimize and improve formation *(24)*. Drainage should be controlled by proper fabric design, such as multi-layer fabrics, so that retention does not suffer.

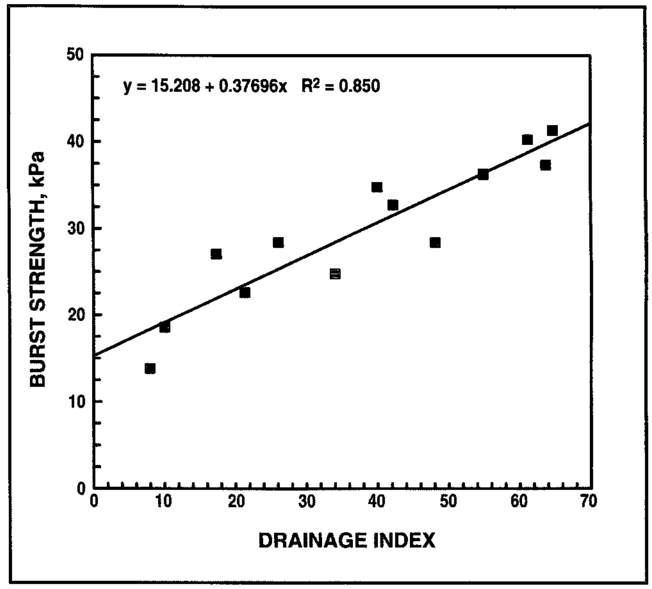
Effect of fiber support

A statistical model was developed by Beran *(13)* to determine the fiber support capability of forming fabrics. Although Beran's work was done mainly with single layer fabrics, the fiber support index (FSI) is

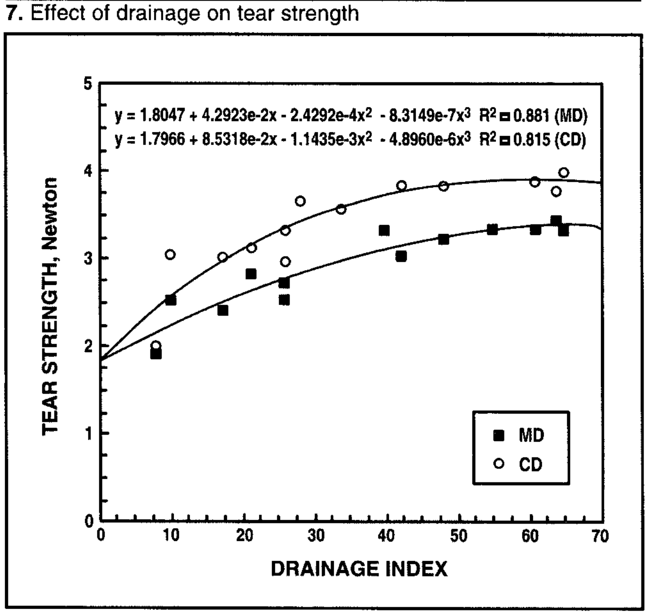
5. Effect of drainage on tensile strength



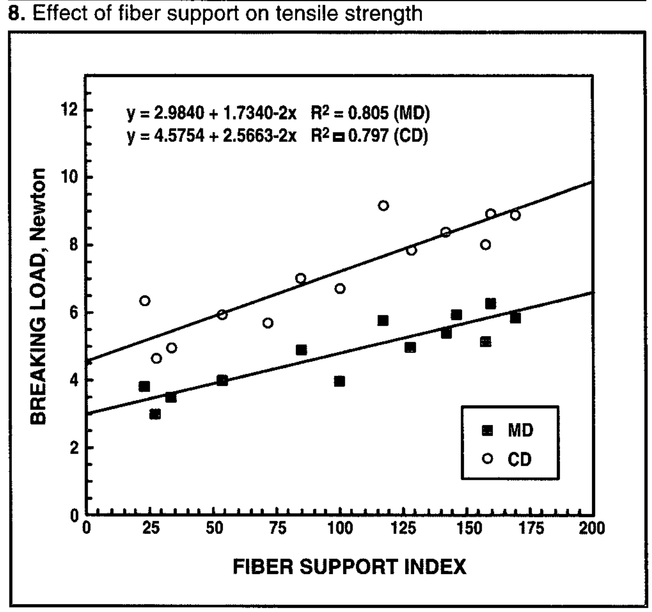
6. Effect of drainage on burst strength



7. Effect of drainage on tear strength

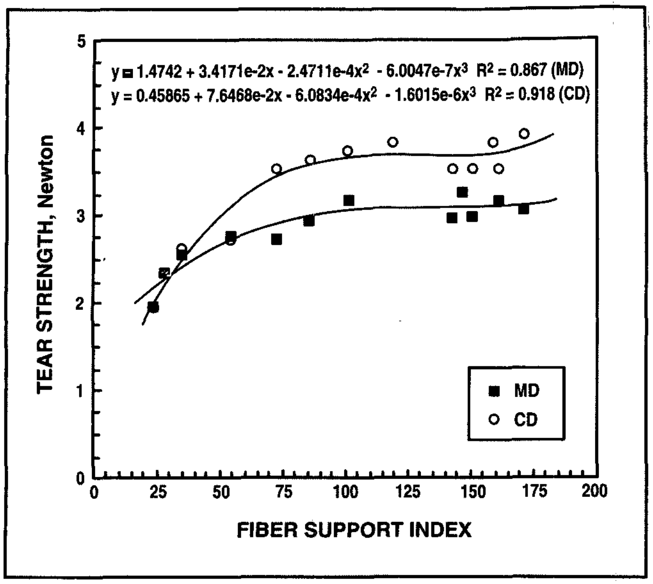


8. Effect of fiber support on tensile strength

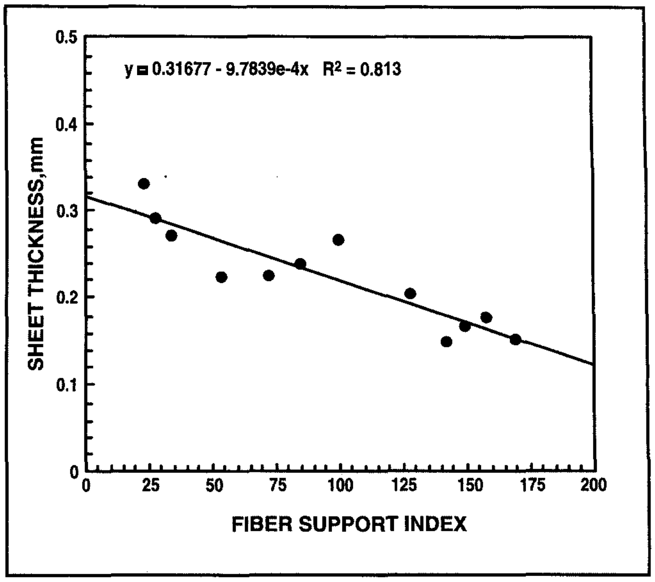


widely used for multilayer fabrics as well throughout the industry. The higher the fiber support index, the more the fabric supports the fibers from falling below the plane of the surface of the fabric. Fibers supported above the plane of the fabric interact more with other fibers than do fibers that are allowed to fall below the plane of the surface of the fabric. This is made clearer by the rationalization that there are no other fibers to interact with below the surface of the fabric. **Figures 8 and 9** support this theory by demonstrating the increase in tensile and tear strengths of the sheets. This can also be related to the fact that there is a decrease in the thickness of the sheet as the fiber support increases. The shape, number, and location of knuckles that are formed by the cross-overs between the MD and CD yarns play an important role in fiber support as well as fabric operating characteristics and paper machine performance. More fibers supported above the plane of the fabric surface by knuckles means more fibers are kept in the same plane. The greater number of knuckles means more fiber support. Not only does this decrease thickness, but also it increases fiber interaction which in turn increases tensile and tear strengths. The relationship between

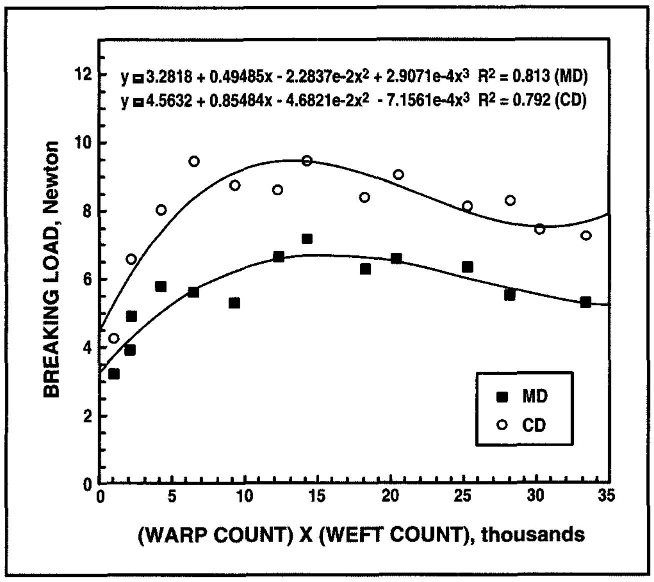
9. Effect of fiber support on tear strength



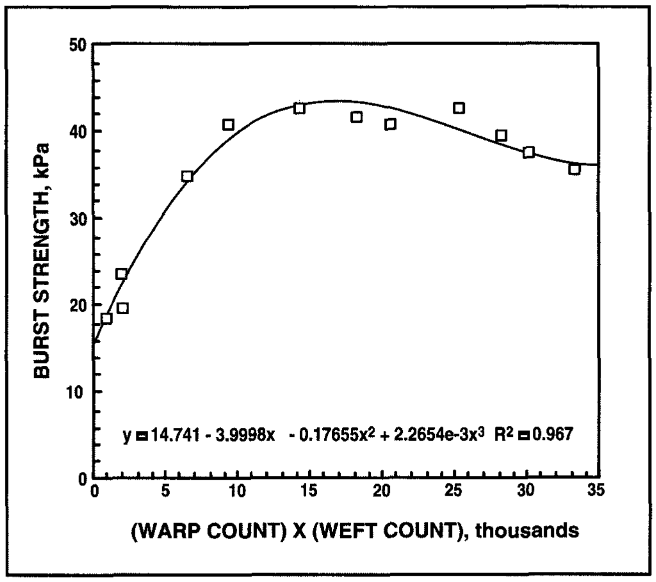
10. Relation between fiber support and sheet thickness



11. Effect of fabric density on tensile strength



12. Effect of fabric density on burst strength



sheet thickness and fiber support index is shown in **Fig. 10**.

Running forming fabrics with the long, dominating CD knuckles on the sheet side provides easier bridging for the fibers coming from the slice. The fibers, which are oriented in the MD direction, are better supported by the perpendicular CD yarns. This running attitude enhances sheet release and improves formation characteristics.

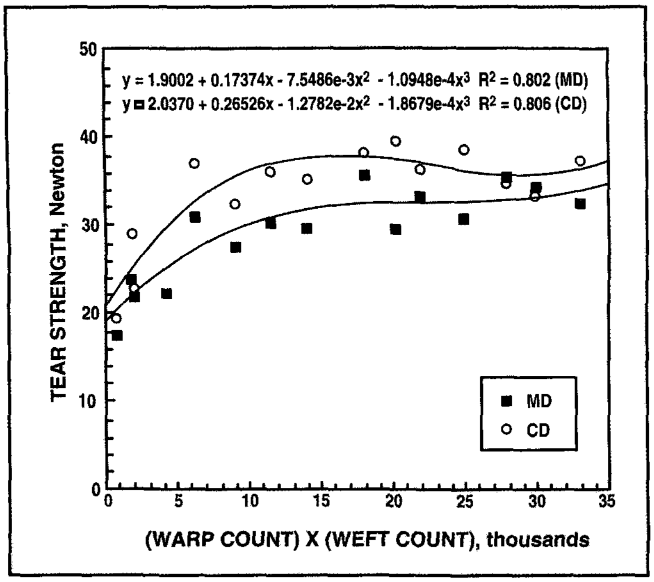
Effect of fabric thickness

The most noticeable effect of fabric thickness was in the uniformity of the sheet. Thicker fabrics are more stable and they allow transmissivity, which is the water flow in the plane of fabric. As a result of more uniform drainage, a more even formation is obtained. This implies that thicker fabrics more readily produce an even sheet. Ridges, which are more likely in fine forming fabrics, could be the cause of ridges in finished paper.

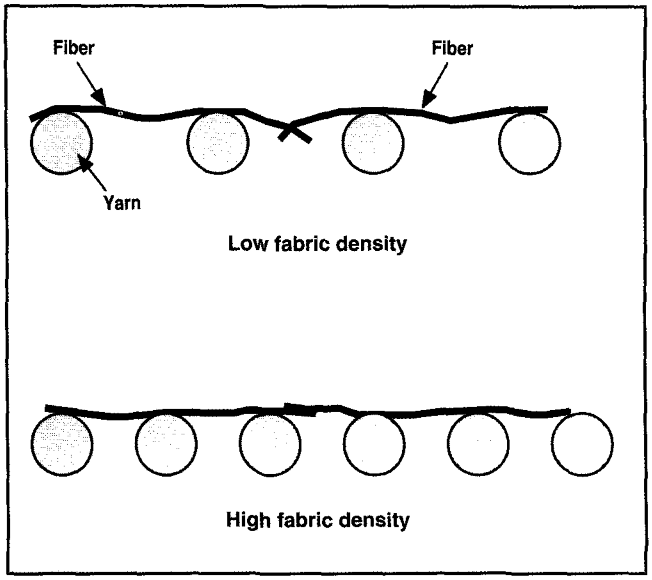
Effect of fabric density (warp and weft count)

As the warp and weft count increase, the fabric becomes finer. This property was found not only to affect the strength of the sheet, but also the thickness. Maximum breaking load, burst, and tear strengths (**Figs. 11, 12, and 13**, respectively) reach a

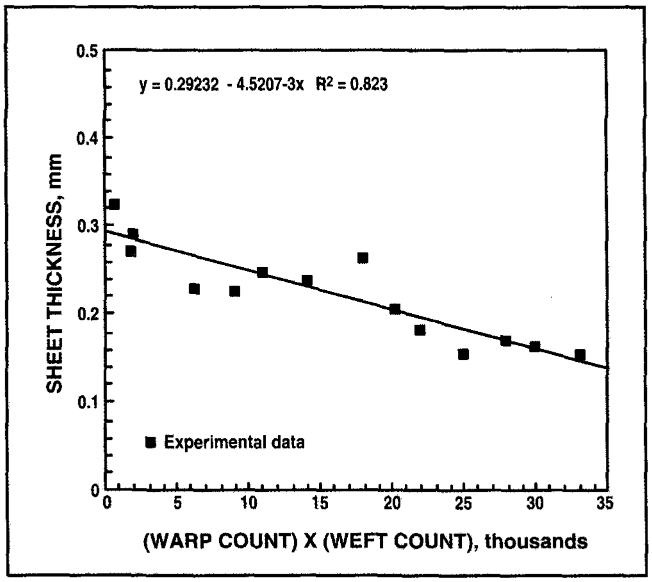
13. Effect of fabric density on tear strength



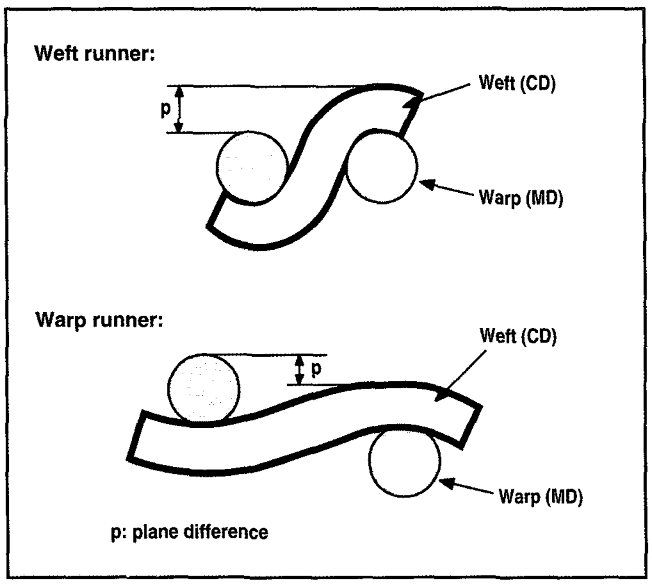
14. Fiber entanglement and fiber support



15. Sheet thickness vs. fabric density



16. Plane difference in forming fabrics



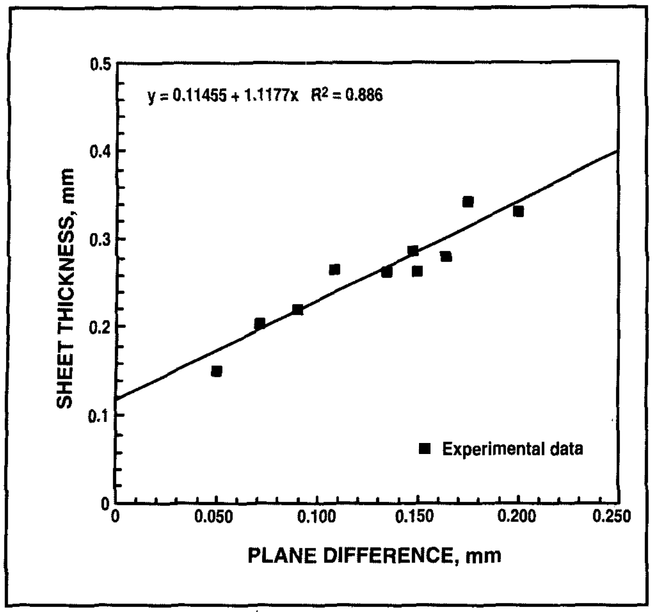
maximum value, then slightly decrease or level off. This is explained by the fact that as the hole size in the fabric becomes smaller, more fibers are supported above the plane of the fabric surface. This corresponds to the relationship between fiber support index and sheet strength. Once these holes are sufficiently small, bleeding (fibers falling below the plane of the surface of the fabric) is reduced and fiber interaction is maximized. When the fabric density is increased further, fiber bleeding may be minimized or eliminated such that there is less entanglement of fiber ends due to higher fiber support, as shown in **Fig. 14**. This explains the slight decrease in paper strength in Figs. 11–13 at high fabric densities.

Sheet thickness (**Fig. 15**), however, follows an inverse relationship to fabric density. Fiber support index is directly related to warp and weft count, and as the fiber support index increases, the sheet thickness decreases. This was due to all fibers being restricted to the same plane.

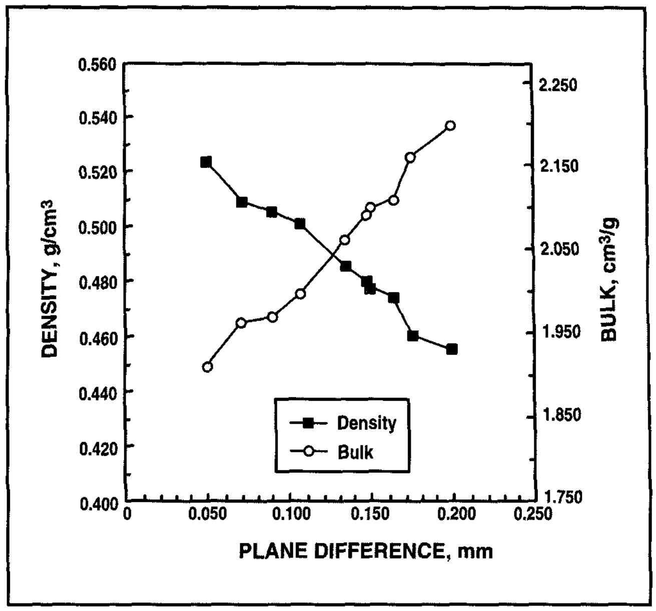
Effect of plane difference on sheet thickness and density

Plane difference of a forming fabric is defined as the difference in distance between the warp and weft yarns on the fabric surface, i.e., dif-

17. Effect of plane difference on sheet thickness



18. Effect of plane difference on sheet density and bulk



ference in knuckle heights of the MD and CD yarns, as shown in **Fig. 16.** Knuckle height can be controlled by yarn diameter, weave density, and heatsetting conditions such as tension. Too much of a knuckle height can cause some papermaking problems including fiber stapling, bleed through, and wire mark. In single layers, one side of the fabric has long CD knuckles and the other side has long MD knuckles if the weave is not balanced. Some fabrics are weft runners—which means that weft yarns are higher than the warp yarns, and some fabrics are warp runners—which means that warp yarns are higher than the weft yarns. There is a direct relationship between the plane difference of a fabric and the resulting sheet thickness. If the plane difference is large, then there is enough room for z-direction fiber orientation which increases the sheet thickness, as shown in **Fig. 17.** This is an advantage in tissue and toweling where thickness is desired *(25)*. From **Fig. 18**, it is seen that sheet density decreases as the plane difference increases. This results in an increase in bulk of the sheet, which is again a desired property for tissue. However, for coated papers, high sheet density is required for coating quality. Highly porous sheet structure causes dewatering of the coat rapidly and very open sheet structure absorbs the coating completely *(15)*. On a paper machine, other factors that affect sheet density and density gradient are total retention of the fines and fillers and retention uniformity.

Summary and conclusions

The study addressed the topic of forming fabric design in relation to sheet formation and properties. The particular topic covered was the impact of fabric design on the final sheet qualities.

Forming fabrics are an essential part of papermaking and their design, properties, and applications have tremendous effects on paper properties and papermaking process. Proper forming fabrics can increase the productivity, decrease paper machine downtime and increase the bottom line. Therefore, it is crucial for the textile engineer to develop the right forming fabric and for the papermaker to know a good deal about forming fabrics. The successful forming fabric supplier must be able to listen and understand the papermaker.

The design and manufacture of forming fabrics are quite complex. The fabric designer has many variables to play with to meet the requirements of paper machine and paper structure. One important aspect is that some requirements may be conflicting. There is no optimal fabric design that fits all the paper grades best. The fabric designer should optimize the forming fabric properties and tailor the fabric structure for the specific machine and paper grade. In order to do this, the designer has to know the correct relationship between the fabric structure and required paper properties. In this work, experimental data was used to examine this relationship.

The experiments showed that paper strength properties are related to forming fabric design and formation. From the experimental data, the following relationships between sheet properties and forming fabric properties were developed:

1. An increase in air permeability and drainage index yields an increase in sheet strength.

2. An increase in fiber support index yields an increase in sheet strength and a decrease in sheet thickness.

3. Sheet uniformity is related to fabric thickness in a static sheet former.

4. An increase in the number of warp and weft yarns per unit length of fabric produces a thinner sheet.

5. The strength of the sheet can be maximized without maximizing warp and weft count.

6. An increased plane difference in the fabric decreases density and therefore increases bulk.

From the data, it can be seen easily which fabric properties affect sheet quality, but to maximize all the fabric properties at once is hardly possible. Some properties must be sacrificed to improve others. This compromising depends greatly on the specific grade of paper being produced and the quality of that grade of paper. To a large extent, the papermaker can control final sheet properties by selecting the proper forming fabric for every position on the machine. TJ

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