A Study of the Effect of Fiber Length Distribution on the Tear Strength of a Synthetic Fiber Sheet

Kit Funderburk

Western Michigan University

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A STUDY OF THE EFFECT OF
FIBER LENGTH DISTRIBUTION
ON THE TEAR STRENGTH OF A
SYNTHETIC FIBER SHEET

by

Kit Funderburk

A Thesis
Submitted to the
Faculty of the School of Graduate
Studies in partial fulfillment
of the
Degree of Master of Science

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Kalamazoo, Michigan
December 1968
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Kit Funderburk
MASTER'S THESIS

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INTRODUCTION

The tear strength has for many years been an important factor to the paper industry. Its use has been applied to quality control aspects as well as to research studies of fibers and papers.

Regardless of all the studies concerning the tear strength that have been made, the exact effect of different fiber parameters has not been fully resolved. At one time or another, fiber length, cell wall thickness, fiber density, sheet density, fiber stiffness, and fiber strength have been regarded as being critical factors affecting the tear strength. However, the interrelationship between these properties and the tear strength has been found to vary. Where there has been agreement as to the nature of the relationship, there was contradiction as to the relative importance of the properties.

It now appears that fiber length distribution is another factor which might have a critical influence on the tear strength. This property has not previously been correlated to the tear strength. Even though fiber length distribution has not been studied, it could have been an uncontrolled variable, due mainly to the experimental methods used. This overlooked factor could have caused some of the conflicting results reported in previous work.

However, to investigate the effects of fiber length distribution independent of other variables thought to influence the tear strength, a wood pulp fiber system is impossible to control adequately. Therefore, a synthetic fiber system was chosen for this study. Because precise control of the physical properties of the fibers was
possible, any differences in tear strength could be attributed directly to the fiber length distribution effects.
LITERATURE REVIEW

There have been many studies undertaken with the purpose of relating the tear strength of paper to various properties of the fibers. However, there has been doubt about the relationships of the critical factors because of conflicting findings.

The widely accepted theory of the mechanism of tear failure was presented by the Staff of the Institute of Paper Chemistry (1). Elmendorf had developed the method to measure an average of the total tearing force through a given distance. The theory proposed regarded this total force as being the sum of a large number of smaller forces. An analysis was then made of the mechanism by which this energy was dissipated within the sheet.

The energy was regarded as being transformed mainly into two processes: (1) pulling fibers intact from the sheet, and (2) straining fibers until they ruptured. The force required for the former (frictional drag work) was said to be less than that required for the latter (work for fiber rupture). However, the work expended in frictional drag is greater than in rupture due to the greater distance over which the force is applied in pulling fibers out of the sheet. The average tearing force is equal to the sum of these two works divided by twice the length of the line of tear. A later modification was proposed (2) to account for the effect of strains for some distance on both sides of the failure.

In regard to the proposed theory, an increase in frictional drag work will increase the tear strength. Since the frictional
drag work is theoretically proportional to the average fiber length, there should be a positive correlation between tear strength and fiber length. However, the relative importance of fiber length remains in doubt. Many investigators have felt that other physical properties are more important to the tear strength.

A positive correlation between fiber length and tear strength has been reported by numerous investigators (3-10). However, in contrast, in a study of various wood species, Nelson and co-workers (11) have reported no correlation between fiber length and tear strength.

Other investigators have reported a dependence of tear strength on the cell wall thickness of the fibers (12-16). It has been found that an increase in cell wall thickness results in an increased tear strength, probably due to less bonding and increased fiber strength. Fiber length was not considered to be an important factor in affecting tear.

Fiber length and cell wall thickness have also been reported as having a dual relationship to tear strength, but the contribution of each factor differed among investigators. Barefoot and co-workers (17) and Watson (18) reported that the most important factor was cell wall thickness, with fiber length showing considerably less importance. Dinwoodie (19) reported that the tear strength was slightly more dependent on wood density (i.e., cell wall thickness) than on fiber length but that both factors were important. Cell wall thickness and fiber length have also been shown to be of about equal importance to tear strength (20, 21). Tamalong and Wangaard (20) found that a combination of fiber length, cell wall thickness, and lumen
width could account for a major portion of the tear strength of unbeaten pulp. The cell wall thickness, however, had an inverse relationship to the tear strength which is a contradiction to the tear strength – cell wall thickness relationship discussed above (12-16).

Cell wall thickness has also been studied by employing mixtures of summerwood and springwood, which have naturally occurring differences in cell wall thickness. It was found that an increase in the percentage of the relatively thin-walled springwood resulted in a decrease in the tear strength (22-24).

An indication of a relationship between the distribution of fiber lengths and the tear strength has recently been proposed by the writer (25). It was found that a decrease of approximately 25% in number average fiber length could cause either no change or a decrease in the tear strength, depending upon the distributions of the fiber lengths. Fiber length distributions were mentioned previously in a derivation of a mathematical equation of tearing strength (26). Interrelationships of fiber length distributions with classification fractions of beaten pulp were also studied (9). However, no specific relationships between fiber length distributions and tear strength were determined.

It can be seen that the literature contains many conflicting ideas. Much of the contradictory data has been due to faulty experimental design as mentioned by Dinwoodie (27). For instance, several investigators (4, 11, 13, 17) have attempted to show relationships by comparing different wood species that had a naturally occurring difference in fiber length and/or cell wall thickness. In addition,
each specie would have its own characteristic chemical and physical properties (i.e., vessel segments, ray elements, chemical composition of surfaces, etc.) which may make comparison between single factors useless.

A problem in studying the effects of fiber length has been to find methods for the preparation of samples of different fiber lengths. Sample preparation to date has consisted of passing a dilute suspension of fibers through successively smaller mesh screens in order to obtain classifications by fiber length. However, Kress and Brainerd (28) reported physical and chemical differences in fibers of such classifications. The physical differences were later substantiated (29) by microscopic examination of the fractions which revealed the presence of broken fibers, fines, extraneous materials, etc. in the shorter fiber length fractions. But investigators have still compared tear strengths to fiber classification fractions with no provisions for elimination of this error, except in a study by Clark (3). In this work the fibers were given a pre-classification and only a long fiber length fraction was retained. In this manner, Clark removed the unwanted components and retained, as a beginning point, fibers in which the differences in chemical and physical properties had been reduced. This fraction was subsequently cut and subjected to classification.

However, Clark's study did not eliminate other problems associated with classification techniques. Fiber length fractions have been found to overlap and to have widely different fiber length distributions (9, 30-32). This was the case in the investigation by Funderburk (25), which lead to the proposal of a possible fiber
length distribution - tear strength relationship.

Yet another problem that arises in classification is that fractionation of the sample is not solely dependent upon fiber length (33). Other contributing factors include design of the classifier (32, 34); shape, rigidity, and surface characteristics of the fibers; geometry of the screens and surface characteristics of the wires; hydrodynamic conditions near the screen; and interference and interaction of neighboring fibers (35).

Together with the problems associated with experimental design, the Elmendorf Tear Tester itself has recently come under criticism (36, 37). Questions have been raised as to what is actually being measured. Serious objections to the method also include the question of simulation of the tear in practical use of the sheet and inconsistencies in the failure pattern of the tested sheet. This last criticism would be of interest as it would affect duplication of results. Difficulties encountered in regard to inconsistencies in failure are the splitting and wandering of the line of tear and the dependence of the tearing force per sheet upon the number of sheets torn simultaneously.

It seems unlikely that numerous investigators would differ so greatly as to the fiber length - tear strength relationship unless another factor, uncontrolled and/or unmeasured, had caused the conflicting results. A possible cause for the discrepancies could be the differences in fiber length distributions. The method of obtaining samples is seen to vary for each investigator, either in regard to wood specie used or the method of fiber length separation. These
effects are quite possibly of sufficient magnitude to introduce differences into the final results.
PRESENTATION OF PROBLEM

It is felt that some of the conflicting ideas concerning the influence of fiber length on tear strength can be explained through correct interpretation of fiber length distribution effects. It is possible that previous investigations have been made in which average fiber length effects were obscured by length distribution effects.

By using a synthetic fiber system, fiber length and fiber length distribution can be studied independent of the effects of other variables. The selection of pre-cut fibers would eliminate inconsistencies due to classification, density of the fibers, stiffness, chemical differences, etc. that have been present in studies to date.
General

Sufficient control of fiber length, fiber length distributions, and cell wall thickness is not possible with wood pulp systems. It would be necessary to vary average fiber length while reproducing exactly the other variables. This is extremely difficult to control with wood pulp fibers due to natural variability of fibers and the imperfect methods of fiber fractionation.

However, by employing a synthetic fiber system, all of the variables might be maintained exactly with the variable under study controlled to the desired levels. In investigating the effect of fiber length distributions on the tear strength of synthetic fiber sheets, it is possible to maintain an exact duplication of average fiber length, fiber diameter, fiber strength, extent of bonding, and other physical properties which might also affect the tear strength. The results of such an investigation would show clearly if the fiber length distributions affected the tear strengths.

Whether the synthetic fiber system exactly represents the wood pulp system is probably not of prime importance. The mechanism of tear failure is essentially dependent upon the same factors in a synthetic sheet as in a pulp sheet. A synthetic fiber sheet is composed of random oriented fibers bonded to each other by a binder. Sheet failure will result from either a rupture of bonds or of fibers. The tearing force will be expended in frictional drag work or in work to rupture fibers similar to the tear mechanism in a pulp sheet.
General qualitative results with synthetic fibers could be applied to a pulp system and quantitative results for the particular synthetic system could be obtained.

Different fiber length fractions of pre-cut synthetic fibers were used to study the effects of fiber length distribution on tear strength. Handsheets were formed from fractions of each average fiber length. Bonding was controlled to a level comparable to pulp sheets by adding an external binder. The distributions were varied by adding the shortest fiber length fractions to each of the longer fractions, thereby shifting the distributions toward shorter average lengths. The tear strengths of the unblended and blended handsheets were then determined by the standard Elmendorf-Tappi Method.

The addition of increasing amounts of shorter fibers decreased the number and weight average fiber lengths. If fiber length distribution was not important to tear strength, one would expect a decrease in tear strength as reported in many previous studies. However, if either no effect or an increase in tear strength resulted, then fiber length distribution would be proven to be a significant factor in tear strength.

Materials

Fibers

Polyester fibers were chosen for this work because their physical properties generally correspond to those of cellulosic material, with the exception of elongation. Typical properties are given in
Appendix I. The availability of information describing the use of polyesters in papermaking (38-43) and the availability of the fibers were also positive factors in this selection.

The fibers were supplied pre-cut to lengths applicable to paper-making by Microfibers, Inc., Pawtucket, Rhode Island. Five fiber length fractions were used with a number average fiber length ranging from about one to six millimeters. The fibers were of circular cross-sectional shape and 3.0 denier (g./9000m). The fiber lengths of each fraction were somewhat distributed about the average. The distributions obtained by machine cutting were presumed to be much narrower than could be obtained from a classification of wood pulp fibers.

*Dispersing Agents*

In a water suspension the polyester fibers floated to the surface and roped together upon agitation. In order to disperse small amounts of fiber for preparing microscope slides, a 0.05% solution of methyl cellulose was used as the dispersing medium.

The methyl cellulose solution was found to be inadequate to disperse fibers in large volumes. The difficulty in dispersion also increased with increasing fiber length. Upon experimentation with wetting agents and/or surface active agents, it was found that a 0.5% solution of Triton X-100\(^1\) gave favorable dispersion character-

\(^{1}\)Trademark of Rohm and Haas Company. Triton X-100 is a non-ionic alkyl aryl polyether alcohol supplied at 100% concentration (44).
istics. Careful handling of the fiber dispersions was necessary because of the tendency of Triton X-100 to cause foaming.

Binder

Bonding of the synthetic fibers was accomplished with a melamine-formaldehyde type resin\(^1\). It was diluted to 5.0% solids for use as a bonding agent. Mircoscopic examination of sheets bonded with resin solution of 5.0% concentration revealed that both fiber rupture and fiber pull-out were occurring in sheet failure. Small amounts of dyed fiber were added to the sheets, and observation of the dyed fibers crossing the line of tear revealed whether the fiber had ruptured or was pulled intact from the sheet. It was found that approximately 40% of the observed fibers failed by rupture which is comparable to the levels found for paper webs (49). Levels higher than 5.0% produced excessive bonding as evidenced by the fact that the sheets were very brittle.

The synthetic fiber sheets were dipped briefly in the 5.0% resin solution, pressed, and then subjected to heat and pressure in order to cure the resin. On evaporation of the carrier (water) the polymer which it contained concentrated at the crossover points of the fibers by capillary action (39). It was deposited at these points and remained after removal of the carrier. The bonding process was then completed by additional heat and pressure which cured the resin. Approximately 1% of the total weight of the sheets was resin.

\(^1\)Parez Resin 613. Supplied by American Cyanamid Company @ 76% solids and 7.6 pH (45).
Methods

**Fiber Dispersion**

To disperse small amounts of fiber for microscope slide preparation, approximately 0.25 grams of fiber was shaken in about 200 ml. of 0.05% methyl cellulose solution.

In order to disperse a greater amount of fiber in a larger volume for sheet making, a 0.5% solution of Triton X-100 was used. For each sheet that was to be made, 2.000 ± 0.005 grams of fiber was weighed with an automatic balance and placed in an individual envelope. In making blends of fiber fractions, each fraction was weighed such that the total weight of both fractions blended was 2.000 grams. Blends were made by adding 5.0%, 12.5%, and 25.0% by weight of the shortest average fiber length fraction to each of the longer fractions. The fiber was added to 1990 ml. of water and stirred briefly in order to loosen fiber bundles. The fiber suspension was then agitated at high speed with a laboratory stirrer. Ten milliliters of Triton X-100 was added when agitation was begun. Mixing was continued until all the fibers were dispersed (approximately four to five minutes).

**Average Fiber Length and Distribution**

A small amount of fiber dispersed in the methyl cellulose solution was removed with a pipet and placed on glass microscope slides. The slides were then heated at 60°C. until all water was removed. Each slide contained about 20 fibers.
A projection procedure was used for fiber length determination. The projection magnification (approximately 70 dia.) was standardized by projecting a grid of known spacing on a screen in order that the distance between grid scale separations was conveniently measurable. The grid was removed and the microscope slides containing the dried fiber were placed in the identical position. The projected fiber images were marked on a large sheet of paper (screen) for later measurement.

The traced images of the fibers were measured with a Dietzgen map measurer which was calibrated against the grid previously projected on the screen (1 scale division on map measurer = 0.05 mm.). Fiber lengths were determined accurately to 0.05 mm. As a fiber length was measured it was entered in a tally sheet corresponding to the fiber length in millimeters. (See Figure 1). Two hundred fibers were measured for each determination.

The total number of fibers of each fiber length was used to calculate the average fiber lengths of each fraction. For graphical representation of each fiber length distribution a grouping of fiber lengths corresponding to 0.20 mm. was used.

The number average fiber length ($L_n$) was determined by

$$L_n = \frac{\sum n_i l_i}{\sum n_i}$$

where $n_i$ = number of fibers of a given fiber length

$l_i$ = fiber length in mm.

The weight average fiber length ($L_w$) was determined by
This equation is derived in Appendix II.

In determining the average fiber lengths of the blended samples, difficulty was encountered in obtaining uniform dispersions of the different fiber lengths. Samples of blended fibers were removed during the sheet forming process, but it was found that it was not possible to make slides with representative quantitative amounts of the different fiber lengths. This difficulty increased as the length differences of the blended samples increased. The problem centered around the pipet transfer procedure. It was extremely difficult to remove representative samples with the pipet and also was difficult to transfer a representative sample to the microscope slides.

Instead of a direct measurement, the average fiber lengths and distributions were calculated based upon the known denier of the fibers, the weight of each fraction added in blending, and the distributions of the fiber lengths for the individual fractions. The method of calculation is shown in Appendix III.

Any fiber lost in the sheet forming process would render this calculation invalid. Therefore, a quantitative determination was made to ascertain that there was no significant loss of fiber. Sheets formed from the shortest average fiber length fraction resulted in a weight loss of less than 0.5%. When this fraction was blended with a longer fiber length fraction even less loss
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Figure 1. Sample tally sheet for recording number of fibers of each fiber length.
would be expected. Because there was such a small loss, the calculation of average fiber length and distribution was considered valid.

Sheet Formation

Handsheets were formed in a British Sheet Mold; however, the traditional wire forming surface was replaced with a fiber glass mesh. The use of the fiber glass forming surface resulted in better formation of the sheet and facilitated removal of the sheet after pressing. The fiber dispersions were poured down the wall of the sheet mold as the mold was filling with water. By pouring down the side, some of the foaming problems were eliminated.

After drainage and sheet formation, the handsheet and the fiber glass cloth were removed. Another fiber glass cloth was placed over the top of the handsheet, resulting in a fiber glass - handsheet - fiber glass laminate which was pressed twice between felts in a Noble and Wood Press, operated with ten pounds of weight on each lever arm.

Sheet Bonding

After formation, the sheet was transferred to a Noble and Wood forming wire which had been cut in an octagonal shape so that it was only slightly larger than the handsheet. A similar wire of exactly the same shape was placed over the top of the handsheet, resulting in a wire - handsheet - wire laminate. The edges of the wires were clipped together so that they might hold the sheet securely between them.
The sheet was then dipped in a shallow pan containing the 5.0% solution of melamine-formaldehyde resin which was used as the binder. Still sandwiched between wires, the sheet was pressed with one roll of a British Sheet Mold couch roll in order to remove excess bonding solution. The handsheet was again transferred between two fiber glass cloths and additional resin solution was removed by pressing once between rubber wringer type rolls. After this final press the sheet was removed from the fiber glass cloths and placed between two teflon coated aluminum plates, which afforded a quick release surface after curing of the resin.

The fiber - resin sheet was cured by heating at 375°F. under 200 p.s.i. for two minutes in a Carver Laboratory Press. Pressure was attained hydraulically between two platens, one being fixed in a position against stops. Heating was from two electric heating plates attached to the platens. The temperature of the plates was regulated with thermostats and checked with internal thermometers. Timing was started when 200 p.s.i. pressure had been reached. During the pressing time the temperature dropped slightly due to heat transferred to the aluminum plates.

Sheet Evaluation

Elmendorf Tear

The tear strength was measured using an Elmendorf Tear Tester in accordance with Tappi Standard T414 ts-64. Four sheets were torn simultaneously. The results were reported as

\[
\text{Tear Factor} = \left( \frac{g_F}{g_W} / m^2 \right) \times 100
\]  

(3)
where \( \sigma_f \) = force in grams required to tear a single sheet
\( \frac{\varepsilon_w}{m^2} \) = weight in grams per square meter of test sample
100 = scaling constant

Considering objections to the inconsistencies in failure pattern with the Elmendorf Tear Tester, no result was used in which the line of tear was observed to wander more than 0.25 cm. or to split. It might be noted that the number of such occurrences was very small, with only about one percent of the test results being discarded. By always tearing four sheets simultaneously any inconsistency due to dependence on number of sheets torn was eliminated. By taking these precautions it was felt that a meaningful test result was obtained.

**In-Plane Tear**

Tear strength was also determined by the In-Plane Method, following the suggested procedure of Van Den Akker (37). Testing was done with an Instron Universal Testing Instrument equipped with specially made wide clamps. The sample was clamped for testing as shown in Figure 2.

![Figure 2](not to scale)
Tensile strength was determined with an Instron Universal Testing Instrument. The loading was accomplished by a moving crosshead holding the sample clamp. This applied the load at a preset speed. The load applied was measured with a strain gauge and the output was transferred to a recording pen. The recording chart was driven simultaneously at a preset speed ratio with respect to the crosshead speed. The recording pen was set to return at either sample rupture or a sudden change in the slope of the loading curve.

Sample strips were cut 0.5 inches wide. The instrument was operated with a 3 cm. initial jaw separation, 5 cm./min. crosshead speed, 50 cm./min. chart speed, and 10 kg. full scale load.

Results were reported as Breaking Length.

\[ \text{B.L.} = \frac{200,000p}{3r} \]  

where B.L. = breaking length (m.)

p = load to break (kg.)

r = basis weight (g./m.\(^2\)).
PRESENTATION AND DISCUSSION OF RESULTS

The results of fiber length distribution measurements for the fractions used in this study are shown in Figure 3. The fractions S (short length), M (medium length), L (long length), and VL (very long length) are those used individually for preparing the initial unblended handsheets. The width and overlap of the fiber length distributions can also be seen from Figure 3. This degree of separation of each fraction is much greater than can be obtained through classification of wood pulp fibers as shown by the typical wood fiber length distribution curve (dashed line) Figure 3 (25).

Fiber length blends for handsheets were made by adding quantitatively the VS (very short length) fraction to the S, M, L, and VL fractions. The VS fraction was very much narrower in fiber length distribution. Therefore, it was possible to produce blends with widely different distributions by adding the VS fraction. The distributions of fiber lengths that resulted from the blending of fractions are shown in Figures 4-15. The corresponding number and weight average fiber lengths for all fractions and blends are given in Table I.

The relationship found between Tear Factor and the average fiber length of the unblended handsheets is shown in Figure 16 as Curve A and in Table II. Curves B and C plotted from data found by Clark (3) fit the equation

\[ \text{Tear Factor} = \frac{k_4 L_w^{1.5}}{d} \]  

where \( k_4 \) = constant
\[ L_w = \text{weight average fiber length, mm.} \]
\[ d = \text{density, g./cm}^3. \]
Total Count = 200 Fibers For Each Fraction

Figure 3. Fiber Length Distributions of Initial Fractions.

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TABLE I

AVERAGE FIBER LENGTHS

Number Average Fiber Length (mm).
Weight Percent of VS Fraction Added for Blends

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Weight Average Fiber Length (mm.)

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<td>3.63</td>
<td>3.30</td>
</tr>
<tr>
<td>L</td>
<td>4.65</td>
<td>4.49</td>
<td>4.29</td>
<td>3.84</td>
</tr>
<tr>
<td>VL</td>
<td>6.14</td>
<td>5.91</td>
<td>5.58</td>
<td>4.98</td>
</tr>
</tbody>
</table>

TABLE II

TEAR STRENGTHS OF UNBLENDED HANDSHEETS

<table>
<thead>
<tr>
<th>Fraction</th>
<th>No. Ave. Fiber Length (mm.)</th>
<th>Wt. Ave. Fiber Length (mm.)</th>
<th>Tear Factor$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>2.43</td>
<td>2.49</td>
<td>133 ± 6</td>
</tr>
<tr>
<td>M</td>
<td>3.89</td>
<td>3.93</td>
<td>179 ± 10</td>
</tr>
<tr>
<td>L</td>
<td>4.60</td>
<td>4.65</td>
<td>195 ± 13</td>
</tr>
<tr>
<td>VL</td>
<td>6.09</td>
<td>6.14</td>
<td>225 ± 9</td>
</tr>
</tbody>
</table>

$^1$ Tear factor ± standard deviation.
Total Count - 1000 Fibers

Fiber Length Distribution of a Blend of S and VS (5.0% by weight).

Figure 4.

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Figure 5. Fiber Length Distribution of a Blend of S and VS (12.5% by weight).
Figure 6. Fiber Length Distribution of a Blend of S and VS (25.0% by weight).
Figure 7. Fiber Length Distribution of a Blend of M and VS (5.0% by weight).
Figure 8. Fiber Length Distribution of a Blend of M and VS (12.5% by weight).
Figure 9. Fiber Length Distribution of a Blend of M and VS (25.0% by weight).

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Figure 10. Fiber Length Distribution of a Blend of L and VS (5.0% by weight).

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Figure 11. Fiber Length Distribution of a Blend of L and VS (12.5% by weight).
Figure 12. Fiber Length Distribution of a Blend of L and VS (25.0% by weight).
Figure 13. Fiber Length Distribution of a Blend of VL and VS (5.0% by weight).
Figure 14. Fiber Length Distribution of a Blend of VL and VS (12.5% by weight).

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Figure 15. Fiber Length Distribution of a Blend of VL and VS (25.0% by weight).
Figure 16. Relationship Between Tear Strength and Average Fiber Length of Unblended Handsheets.

10 Millimeters to the Centimeter

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The data found in this study (Curve A, Figure 16) fit the equation

$$\text{Tear Factor} = J L^{.58}$$

where $J = \text{constant}$.

An estimation of the data from a relationship between tongue tear and fiber length of synthetic fibers (textryls of Dacron), published by Hentschel (42), yields an approximate fit to the equation

$$\text{Tear Strength} = J_1 L^{.85}$$

where $J_1 = \text{constant}$

$L = \text{fiber length, mm.}$

The data obtained in this study is in agreement with the generally accepted correlation between tear strength and fiber length. Except for isolated studies, it has been shown that the tear strength increases with increasing fiber length. The data of this study supported this relationship and indicated that the initial synthetic fiber sheets approximated the tear mechanism of wood fiber papers.

However, when handsheets made from blends of the fiber lengths were tested, it was found that different relationships existed, as shown in Figure 17 and Table III.

According to the relationship supported by the data in Figure 16, an addition of fibers which results in a reduction of average fiber length should be accompanied by a decrease in the tear strength if fiber length distribution is not involved. When increasing amounts of very short fiber (VS) were added to fraction $S$, a decrease in the tear factor was found as expected (Figure 17). However, as very short
Figure 17. Relationship Between Tear Strength and Percent by Weight of Very Short Fibers Added for Blends.
TABLE III
TEAR STRENGTHS OF BLENDED HANDSHEETS

Tear Factor

<table>
<thead>
<tr>
<th>Fraction</th>
<th>0%</th>
<th>5.0%</th>
<th>12.5%</th>
<th>25.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>133 ± 6</td>
<td>116 ± 8</td>
<td>124 ± 7</td>
<td>112 ± 7</td>
</tr>
<tr>
<td>M</td>
<td>179 ± 10</td>
<td>191 ± 8</td>
<td>193 ± 10</td>
<td>179 ± 10</td>
</tr>
<tr>
<td>L</td>
<td>195 ± 13</td>
<td>202 ± 10</td>
<td>215 ± 8</td>
<td>192 ± 11</td>
</tr>
<tr>
<td>VL</td>
<td>226 ± 9</td>
<td>237 ± 14</td>
<td>258 ± 11</td>
<td>245 ± 15</td>
</tr>
</tbody>
</table>

1 Tear Factor ± standard deviation.

fibers (VS) were added to fractions of increasing initial fiber lengths (M, L, and VL) different relationships were found. The addition of very short fibers resulted in initial increases in the tear factor. A maximum level was reached, whereupon the tear factor decreased with further additions of the VS fraction. As the fiber length of the initial unblended fraction increased (M>L>VL), greater amounts of very short fiber could be added before maximum tear strength was reached. The greater the difference in fiber length between the initial fraction and the very short fibers added, the greater was the increase in the tear strength.

The same relationship was shown when the tear factor was plotted against number or weight average fiber length (Figures 18 and 19). The data are presented in Table IV. The addition of very short fibers had a much greater effect on the resultant number average fiber
Figure 18. Relationship Between Tear Factor and Number Average Fiber Length of Blended Handsheets.

Also see Figure 20.
Figure 19. Relationship Between Tear Factor and Weight Average Fiber Length of Blended Handsheets.
# TABLE IV

AVERAGE FIBER LENGTHS AND RESULTANT TEAR FACTORS

OF BLENDED HANDSHEETS

<table>
<thead>
<tr>
<th>Fraction</th>
<th>VS Fiber Added (Weight %)</th>
<th>No. Ave. Fiber Length (mm.)</th>
<th>Wt. Ave. Fiber Length (mm.)</th>
<th>Tear Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0</td>
<td>2.43</td>
<td>2.49</td>
<td>133 ± 6</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>2.35</td>
<td>2.46</td>
<td>116 ± 8</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>2.25</td>
<td>2.36</td>
<td>124 ± 7</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
<td>2.11</td>
<td>2.24</td>
<td>112 ± 7</td>
</tr>
<tr>
<td>M</td>
<td>0</td>
<td>3.89</td>
<td>3.93</td>
<td>179 ± 10</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>3.60</td>
<td>3.81</td>
<td>191 ± 8</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>3.24</td>
<td>3.63</td>
<td>193 ± 10</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
<td>2.79</td>
<td>3.30</td>
<td>179 ± 10</td>
</tr>
<tr>
<td>L</td>
<td>0</td>
<td>4.60</td>
<td>4.65</td>
<td>195 ± 13</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>4.17</td>
<td>4.49</td>
<td>202 ± 10</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>3.64</td>
<td>4.29</td>
<td>215 ± 8</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
<td>3.06</td>
<td>3.84</td>
<td>192 ± 11</td>
</tr>
<tr>
<td>VL</td>
<td>0</td>
<td>6.09</td>
<td>6.14</td>
<td>226 ± 9</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>5.28</td>
<td>5.91</td>
<td>237 ± 14</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
<td>4.37</td>
<td>5.57</td>
<td>258 ± 11</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
<td>3.45</td>
<td>4.98</td>
<td>245 ± 15</td>
</tr>
</tbody>
</table>

¹ Tear Factor ± Standard Deviation.
length than on the weight average. This was significant in a consideration of whether number or weight average fiber length has greater significance in predicting the effect of fiber length on tear. It has generally been accepted that weight average fiber length has greater significance because of the suspected unimportance of the shorter fibers (3). However, this study indicates that if the shorter fiber added is greatly different in length than the initial fraction, the effect of the short fibers is increased.

From Figures 18 and 19 it is evident that a number or weight average fiber length should not be used alone to predict tear strength. For example, from the curves in Figure 18, a single average fiber length of 3.6 mm. characterizes three significantly different tear factors (i.e., 191, 236, and 250). These three tear strengths associated with approximately 3.6 mm. average fiber length have different distributions of fiber lengths. In Figure 18 the data points labeled X, Y, and Z correspond to handsheets having the fiber length distributions similarly labeled in Figure 20, which are fractions represented by a composite of Figures 7, 11, and 15. The distribution curves have approximately the same average fiber length (X = 3.60 mm. Y = 3.64 mm., Z = 3.45 mm.). It is concluded that in order to predict tear strengths from average fiber length data, information concerning fiber length distribution also must be considered.

It might be argued that the tear strength of the Z blend was greater than X or Y because the increased lengths of the initial fraction made up for their decrease in number, and also, that the very
Figure 20. Fiber Length Distributions of Three Blends Having Approximately The Same Average Fiber Length.
short fibers did not contribute to the strength properties. However, it must be remembered that the strength of the Z blend itself was higher than the tear strength of the VL fraction of which it was a blend. The Z blend had fewer long fibers, many more short fibers, and still yielded a tear strength greater than the VL fraction.

It is suggested that the observed increase in tear strength upon addition of short fibers was due to improvements in the distribution of the fibers (formation) by a "filling in" action. This "filling in" effect has been previously considered as a contributing factor to strength properties (30). It is postulated that as the number of shorter fibers increases the sheet structure becomes more continuous and uniform. This reduces the chance of weak spots which can decrease the strength properties. Yet a sufficient quantity of long fibers remains to provide for a distribution of applied force through a large area.

The following explanation of the observed results is feasible. The unblended S fraction was initially well structured so that the addition of short fibers did not improve the sheet structure. As the fiber length of the initial samples increased (S→M→L→VL), the formation became poorer so that very short fibers were needed to bridge between the longer fibers and increase the strength. However, a maximum was reached at which point further additions of very short fiber could no longer improve formation. At this point the very short fibers were replacing longer fibers in the structure and the tear strength decreased.
Because there was no visible change in formation or orientation of the fibers in the sheet, the formation improvement did not appear to be the same as the visible formation characteristics of paper, but probably affected "internal" formation on a micro-level. It is felt that the internal structure of the sheet can become more continuous because of the bridging of the shorter fibers.

It was possible to further substantiate the "filling in" effect by a determination of tensile strength of the same blended and unblended handsheets. Tensile strength has been associated with a weak link theory (46). The weak link in this case is caused by a structure deficiency of the sheet. If short fibers were "filling in" the structure, the possibility of a weak leak would decrease. The "filling in" should therefore cause an increase in tensile strength. Figure 21 and Table V show that there was a significant increase in the breaking length when a small amount of very short fiber was added to fractions L and VL. These fractions were of the longest fiber length, and formation and structure problems discussed previously (p. 45) could account for a high probability of a weak link. It was concluded that the very short fibers were actually filling in the structure with the result of higher strength properties.

Preliminary investigations were made to determine if the In-Plane Tear (37) results corresponded to those obtained by the Elmendorf Method. It was concluded that the mechanism of tear failure was extremely different for the two methods. No consistent or reproducible data was obtained using the In-Plane Method. It was speculated that the In-Plane test was too greatly influenced by
Figure 21. Relationship Between Breaking Length and Percent by Weight of Very Short Fibers Added for Blends.
### TABLE V

**BREAKING LENGTH OF BLENDED HANDSHEETS**

<table>
<thead>
<tr>
<th>Fraction</th>
<th>0%</th>
<th>5.0%</th>
<th>12.5%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1860</td>
<td>1720</td>
<td>1585</td>
<td>1487</td>
</tr>
<tr>
<td>M</td>
<td>2450</td>
<td>2666</td>
<td>2708</td>
<td>2780</td>
</tr>
<tr>
<td>L</td>
<td>2287</td>
<td>3508</td>
<td>2350</td>
<td>2420</td>
</tr>
<tr>
<td>VL</td>
<td>1508</td>
<td>2975</td>
<td>1965</td>
<td>2000</td>
</tr>
</tbody>
</table>

Sample Width 0.5 in.

elongation, the elongation of the polyester fibers being much higher than for cellulosic fibers (Appendix I). Visual inspection of the line of tear from the Elmendorf Method showed the failure to be the result of a combination of fiber rupture and fiber pull-out evidenced by a "clean" line of tear. However those sheets torn in the In-Plane Method were characterized by a much larger amount of pull-out, almost to the exclusion of fiber rupture. The line of tear reflected the fiber pull out as it wandered considerably and was not a "clean" failure.
CONCLUSIONS

By the use of a synthetic fiber system it was possible to study the effect of fiber length distribution on the tear strength, independent of other physical properties.

It was found that the tear strength could be increased to a maximum by the addition of very short fibers to the initial fiber system. This increase was correlated to the change in the fiber length distribution due to the addition of the short fibers. The increase in the tear strength was greater when there was a greater difference between the average fiber length of the initial fraction and of the short fiber fraction added.

The mechanism by which the distribution of fiber lengths affected the tear strength appeared to be due to a "filling in" action of the shorter fibers. Conceivably, the continuous structure of the sheet was improved by the addition of the very short fibers which had a bridging effect, increasing the tear strength.

It has long been assumed that short fibers contributed relatively little to sheet properties as compared to long fibers. However, this study showed that short fibers are of significant importance due to their effect on fiber length distribution. The short fibers increased in importance as they became shorter in relation to the average fiber length of the fiber fraction to which they were added.

Another finding was that a weight average fiber length, which is relatively unaffected by short fibers, is not necessarily the best average fiber length index. This research showed that an addition of
very short fibers to a relatively long fibered fraction could cause an increase in the tear strength, even though the change in weight average fiber length was almost insignificant. In this case a number average fiber length was more meaningful because it reflected the importance of the shorter fibers.
LITERATURE CITED


## APPENDIX I

### TYPICAL PHYSICAL PROPERTIES OF POLYESTER AND COTTON FIBERS (47)

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyester</th>
<th>Cotton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking Length (grams/denier)</td>
<td>2.8 - 5.2</td>
<td>3.0 - 4.9</td>
</tr>
<tr>
<td>Tensile Strength (p.s.i.)</td>
<td>50,000 - 92,000</td>
<td>68,000 - 98,000</td>
</tr>
<tr>
<td>Breaking Elongation (%)</td>
<td>19 - 30</td>
<td>3 - 7</td>
</tr>
<tr>
<td>Elastic Recovery (%)</td>
<td>97 @ 2%</td>
<td>74 @ 2%</td>
</tr>
<tr>
<td></td>
<td>80 @ 8%</td>
<td>45 @ 5%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.38</td>
<td>1.54</td>
</tr>
</tbody>
</table>
APPENDIX II

DERIVATION OF EQUATION FOR DETERMINING WEIGHT AVERAGE FIBER LENGTH ($L_w$).

$$L_w = \frac{w_1 l_1 + w_2 l_2 + w_3 l_3 + \ldots}{W}$$  \hspace{1cm} (8)

where $W$ = total weight of fibers measured

$w = \text{weight of fibers of each fiber length}$

$L = \text{length of fibers (48)}$

If $w_i = n_i \cdot \bar{L} \cdot d$  \hspace{1cm} (9)

where $n_i = \text{number of fibers}$

$L_i = \text{length of fibers}$

$d = \text{denier (wt./length)}$

and $W = \sum w_i$  \hspace{1cm} (10)

then

$$L_w = \frac{n_1 L_1 d_1 + n_2 L_2 d_2 + n_3 L_3 d_3 + \ldots}{n_1 L_1 d + n_2 L_2 d + n_3 L_3 d + \ldots}$$  \hspace{1cm} (11)

\[ L_w = \frac{\sum n_i L_i^2}{\sum n_i L_i} \]  \hspace{1cm} (12)
APPENDIX III
DERIVATION OF EQUATION FOR DETERMINING NUMBER OF FIBERS ADDED FOR BLENDED HANDBLETS

Since 3.0 denier = 3g./9000 m. = 1 g./3 x 10^6 mm.,
and if \( w_a \) = weight of each fraction added for blend (grams),
then
\[
\frac{1}{3 \times 10^6 \text{mm}} \propto \frac{w_a}{L_T}
\]
where \( L_T \) = total length of fibers added for blend

\[ . \ \therefore L_T = \left(3 \times 10^6\right) (w_a) \quad (13) \]

If \( N_a \) = total number of fibers added for blend of each fraction,
\[ \sum n_i l_i \] = total length of known fraction
\[ 200 \] = number of fibers counted in determining \( \sum n_i l_i \),
then
\[
\frac{N_a}{L_T} \propto \frac{200}{\sum n_i l_i}
\]

\[ . \ \therefore N_a = \frac{200 L_T}{\sum n_i l_i} \quad (14) \]

If \( n_i \) = number of fibers of each fiber length of known fraction
\( N_{ia} \) = number of fibers of each fiber length added for blend,
then
\[
\frac{n_i}{200} \propto \frac{N_{ia}}{N_a}
\]

\[ . \ \therefore N_{ia} = \frac{n_i N_a}{200} \quad (15) \]
Substituting for \( N_a \) and \( L_T \),

\[
N_{ia} = \frac{(3 \times 10^4) (N_a X w_a)}{\sum n_i l_i}.
\]  

(16)

\( L_n \) and \( L_w \) can then be calculated from (1) and (2).