4-1967

The Effect of Fiber Length on Tear Strength

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THE EFFECT OF FIBER LENGTH
ON TEAR STRENGTH

by

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A thesis submitted to the

.ty of the Department of Paper Technology

in partial fulfillment

of the

Degree of Bachelor of Science

Western Michigan University

Kalamazoo, Michigan

April, 1967

ABSTRACT: The purpose of this investigation was to study the effect that fiber length had on the tear strength. Of utmost importance to the results of this study was the elimination or controlling of variables which have appeared in all related studies to date. With this in mind, an experimental procedure was drawn up which would eliminate or control the variables. Long, whole fibers were isolated, formed into handsheets, and dried without having been pressed. The handsheets were then cut in order to reduce the fiber length. Cutting of the fibers was done with a paper cutter and was followed by average fiber length determination by projection. The cut fibers were then classified and the classification fractions were retained for making handsheets for testing.

It was found that the distribution of the fiber lengths was as important to the tear test results as was average fiber length as constant dependence on average fiber length alone could not be found. Only when considering both average fiber length and distribution of the fiber lengths could a sensible correlation be deduced for the effect on the tear test. Studies of how elongation and tensile absorption energy are effected by a difference in fiber lengths and a study of the effect of basis weight on elongation were made, and no correlation was found for any of the factors mentioned.

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HISTORICAL BACKGROUND AND DEVELOPMENT OF THE PROBLEM: There have been many articles published showing the effects of fiber length on tear strength. Upon closer inspection, however, these articles reveal inconsistencies which could effect the outcome of the results, as many experiments have been made without concern for certain variables. Therefore, an investigation has been made in which all variables except fiber length are eliminated or controlled.

Otto Kress and Forrest W. Brainerd (1) reported physical and chemical differences in structure of fiber classification fractions. Renata Morton and S. D. Alexander (2) recognized the fact that fiber classification fractions were different but still used this process to obtain different fiber lengths for their study. Therefore, their work was not a study of fiber length alone, but a study of chemical and physical differences as well.

James d'A. Clark (3) took the difference in classification fractions into account in his study, but he introduced other variables such as using a bleached pulp. Clark isolated long fibers, made handsheets from these fibers, and then cut them with a knife. Different fiber lengths were then obtained by classification. He neglected to specify his experimental procedures, especially in the area of sheetmaking, in which he failed to report the pressing and drying procedure for the sheets which were cut with a knife and then disintegrated for classification. Pressing can increase the bonding of the sheets; this in turn can effect the fibers when they are disintegrated. By increasing the bonding, the fibers would be harder to separate, and when fiber

separation did occur fiber damage could result from the use of more power to disintegrate and/or a longer disintegration time.

A. H. Nadelman (4), with three students from Western Michigan University, carried out a determination of the effect of fiber length on the physical characteristics of handsheets. However, they used beaten pulp and fiber classifications for the selection of samples, thereby introducing two large variables into the results.

J. P. Van Buijtenen, P. N. Jaronson, and D. W. Einspahr (5) used different species of raw material for their investigation into the effect of fiber length on tear strength. This is not a test concerning different fiber lengths, but a study of the properties of different raw material sources.

The tearing force varies erratically from point to point in the sheet. Therefore, Elmendorf developed a method which results in an average of the total force by measuring the energy required to tear the sheet through a given distance, regarding the total force as being the sum of a large number of forces. The work put into the process of tearing is 2Fe, where F is the total tearing force and e is the length of the tear. When a sheet is torn, the energy is dissipated in two processes--fiber rupture and pulling the fiber intact from the mesh of contiguous fibers.

If m is the number of fibers ruptured under tensile stress, w_r is the work to rupture an individual fiber under tensile stress, n is the number of fibers pulled intact from the mesh, and w_f is the work to pull an individual fiber from the mesh, the total work in

tearing is $(mw_r + nw_f)$. Equating this with the energy put into the process, we have

$$F = (mw_r + nw_f)/2e \qquad 1.$$

It was further determined that w_f, the frictional drag work, was very much greater than w_r and that w_f is theoretically proportional to fiber length (6).

The first problem that was presented by a study of fiber length and tear strength was a method by which fibers could be obtained that differed only with respect to fiber length. The problem is therefore one of obtaining different length fibers that have the same physical and chemical properties except for length, and to eliminate or control all other variables and to show the effect that these different fiber lengths have on the tear test results for sheets formed from them.

Long, whole, unrefined fibers were isolated and then formed into handsheets with no pressing of the sheets being done. The handsheets were then cut with a paper cutter, disintegrated, and classified to obtain the different fiber lengths. The fibers obtained from classification were then formed into handsheets for testing.

EXPERIMENTAL DESIGN: In order to eliminate variables such as bleaching in the raw fiber stock and to provide initial fibers of substanial length, samples were taken from a baled, unbleached, softwood Kraft and conditioned at constant temperature and humidity.

The sample pulp was torn into approximately one inch squares and soaked in water for at least four hours. The pulp and water mixture was made up to 2,000 ml. with water at 23 ± 2^{o} C. and then disintegrated at 0.12% consistency for five minutes in the TAPPI Standard Disintegrator. The disintegrated pulp was run through a Bauer-McNett Fiber Classifier for fifteen minutes, using 10 O.D. grams. The first fraction was retained on a 12 mesh screen, all other fractions being discarded. In this manner, all pulp saved is of the same chemical and physical structure.

Using the retained fibers, 2.5 O.D. gram handsheets were made with the British Sheet Mold. Handsheets were couched off the wire with only one roll of the couch roll and no pressing was done on the handsheets. The sheets were then dried between blotter papers at constant temperature and humidity.

The sheets were then cut with a paper cutter, making parallel cuts as close together as possible. Several sheets were not cut and were retained for a control sample. The uncut sheets were torn into approximately one inch squares and soaked in water a minimum of four hours; the cut samples were also soaked in water the same length of time. Cut and uncut samples were then made up to 2,000 ml. with water at 23 ± 2^{o} C. and disintegrated at 0.12% consistency for five minutes

in the TAPPI Standard Disintegrator.

The disintegrated, cut samples were run through the Bauer-McNett Fiber Classifier, 10 O.D. grams for fifteen minutes. 12, 16, 20, and 35 mesh screens were used for retaining the fractions. Samples hereafter are referred to as control, #1, #2, #3, #4, representing the control, 12, 16, 20, and 35 mesh screen fractions respectively.

Handsheets to be tested for tear strength were made from the control sample and the different classification fractions according to TAPPI Standard T 205 m-58. Small samples of fiber from each classification and the disintegrated control sample were retained for making fiber slides. Average fiber length and distribution of the fiber lengths were determined by the projection method.

After the mositure content of the handsheets was determined, they were weighed to determine the basis weight in grams per square meter, oven dry basis. One inch strips were cut from the sheets for testing on the Instron Load-Elongation Tester which was operated with a full scale load of 5 kg., 10 cm. jaw span, 2 cm./min. jaw speed, and 20cm./min. chart speed. Elongation, work, and load to break were recorded.

Tear tests were made on the Elmendorf Tear Tester according to TAPPI Standard T 220 m-60, except that four sheets were tested at once, and a factor of four was used to obtain the force in grams to tear a single sheet. Results were reported as tear factor.

$$\text{Tear Factor} = 100g/r \qquad 2.$$

where g = force in grams to tear a single sheet

r = basis weight in grams per square meter (mositure free basis).

DISCUSSION: In order to check the effectiveness of the method used for fiber cutting, fiber slides were made and microphotographs were taken. For this investigation it was essential that the fibers be cut cleanly and without fiber damage. Flattening of the fiber or frayed ends would introduce variables which would effect the results of the investigation. As seen in Figure 1., the fibers have not been damaged by mutilation and the ends have not been frayed due to a ragged cut. This method of cutting is then seen to be an acceptable method for decreasing the fiber length as it resulted in no fiber damage which would introduce variables into the investigation.

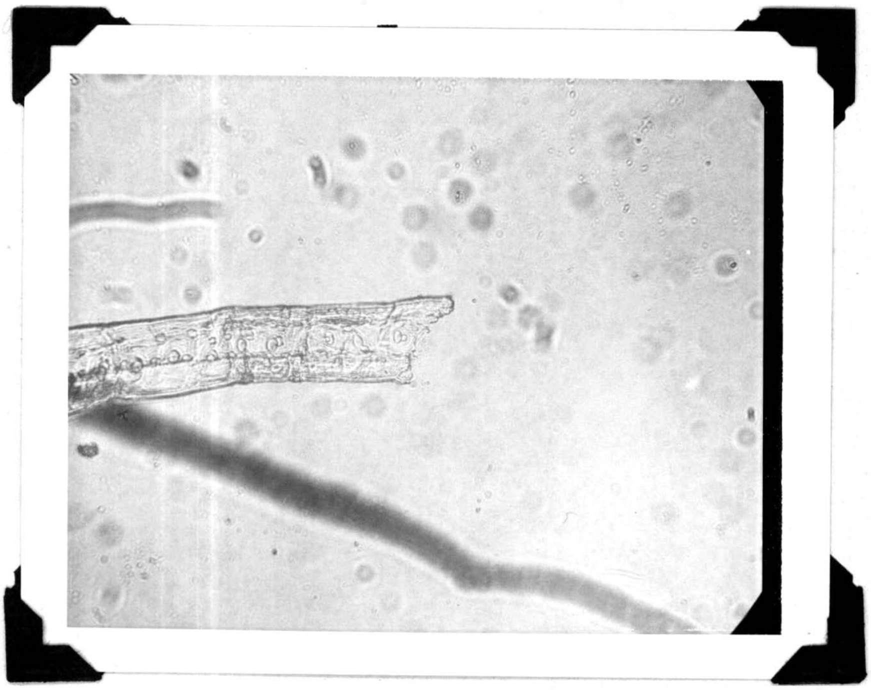


Figure 1. Samples of cut fiber

From previous discussion, several statements can be made regarding the test result analysis.

1. Since all fibers are unbeaten and unrefined, fibrillation and bonding could be considered to be present to a very small degree only.
2. Most of the strength of the handsheets was due to entanglement.
3. Most of the work in the tear test was expended in pulling fibers from the sheet, rather than in fiber rupture.
4. The tear test was, therefore, a measurement of frictional drag work.
5. Frictional drag work is directly proportional to fiber length.
6. The control sample and all classification fraction samples had undergone the same amount of wetting and drying. The control sample differed only in the fact that it contained long, uncut fibers.

A plot of tear factor versus classification fraction (Figure 2.) showed a decrease in tear factor with a decrease in fraction number. Tear factor was not plotted as point values, but was plotted as standard deviation values. The midpoint of the standard deviation line is the average tear factor. Standard deviation was determined as

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \qquad 3.$$

where s = standard deviation

x_i = individual tear factor result

$\bar{x}$ = average tear factor result

n = number of tear factor results.

The control sample is shown in Table II. to have the longest average fiber length. Due to the long average fiber length and the width of the fiber length distribution (Figure 3a.), we would expect a high degree of fiber entanglement, a high frictional drag work under tension, and a correspondingly high tear factor, which was the result.

Comparing the control sample to the #1 fraction, a sharp decrease in the tear factor vs. classification fraction was observed (Figure 2). In the control sample 81% of the fiber lengths are between 2.0 mm. and 3.8 mm., inclusively. In the #1 sample 89% of the fiber lengths are in the same range. In the two samples there was a large overlap of fiber (Figure 3a., 3b.) and not a great decrease in average fiber length (Table II.). Therefore, the large drop in tear factor cannot be attributed to a large decrease of the average fiber length or to a large difference in distribution of the fiber lengths between the two samples. It appears that a critical value of fiber length and distribution necessary for sufficient entanglement to give a high tear strength lies between the control and the #1 sample. The control sample displays a more random and wider distribution than the #1 sample. The more random sample would be expected to give a better formed sheet and a higher tear strength.

Comparing the #1 sample to the #2 sample, no decrease in tear factor vs. classification fraction was observed. However, the true shape of the curve in this portion of the graph might show a slight decrease in tear factor due to the standard deviation values plotted.

There was a large drop in the average fiber length between the #1 sample and the #2 sample (Table II.). Since the tear factor did not decrease relative to the decrease in average fiber length, the average fiber length must not be the total cause of what is happening to the tear factor. Therefore, the observed situation of tear factor not decreasing must be due to the fiber length distributions. The distribution of the #1 sample (Figure 3b.) shows that there was only a very few fibers on the ends of the distribution curve. Therefore, the significant fiber lengths lie in the middle of the distribution where the frequency is high. The distribution of the #2 sample (Figure 3c.) shows that the frequency of the longer and shorter fibers is significantly higher than the corresponding fiber lengths in the #1 sample. Therefore, a better formed sheet could be expected for the #2 sample because the high frequency of all fiber lengths would account for a filling in of the sheet. Therefore, a high tear factor for the #2 sample would be expected instead of the lower tear factor if only average fiber length were considered.

From the #2 sample to the #3 sample, a small drop in tear factor vs. classification fraction was observed. The distribution curves showed more short fibers in the #3 sample than in the #2 sample and an overlap in the center (Figure 3c.,3d.). Because of the average fiber length drop, due to the greater amount of short fibers in the distribution of the #3 sample, there was less frictional drag work and a slightly lower tear factor.

From the #3 sample to the #4 sample, a large drop in tear factor

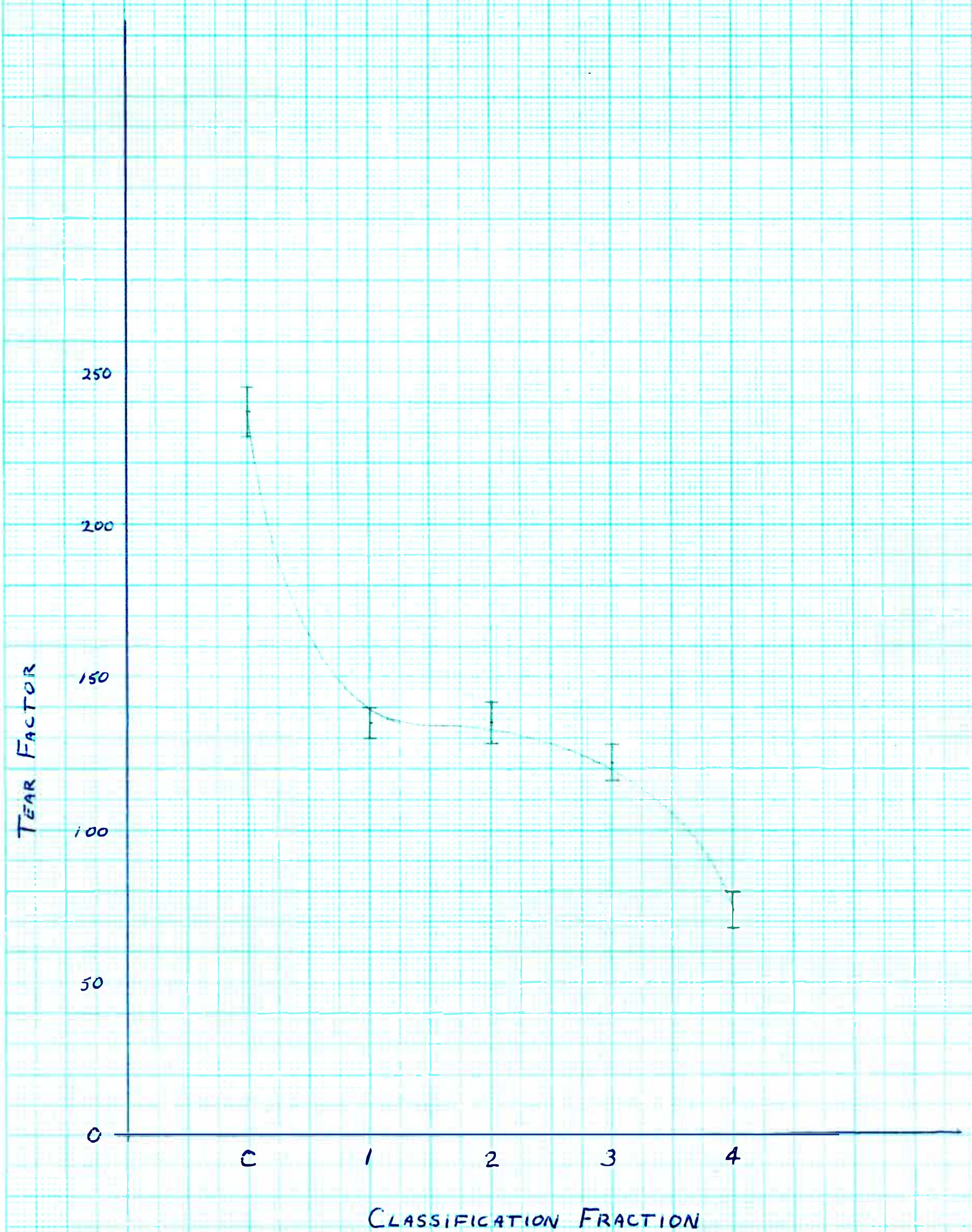
vs. classification was observed. There was very little overlap in the fiber lengths (Figure 3d., 3e.) and a relatively large decrease in average fiber length. Therefore, there was a large decrease in frictional drag work and a large decrease in tear factor.

The first large decrease in the tear factor (control-#1) is theorized to be due to a critical value of fiber length and distribution with regard to fiber entanglement. The average fiber length and the distribution of fiber lengths were reduced enough to pass this critical point at which the sheet strength was greatly reduced due to a decrease in fiber entanglement. Throughout the curve of tear factor versus classification fraction, the average fiber length and the fiber length distributions were both important to the outcome of the results. Averages can be greatly different, but factors concerning the distribution can tend to decrease the importance of average fiber length.

A determination of elongation and tensile absorption energy as related to average fiber length is displayed in Table III. It is thought by some that these properties are correlated with fiber length and thereby correlated with the tear test results. No such correlation was found by this investigation. This did not, however, discredit the assumption. Because of the low degree of bonding of the fibers, an absolutely valid experiment was not carried out; but it did demonstrate that it was of no significance in this investigation. In this investigation the fibers from which the sheets were made had no refining or beating. The sheet and fiber properties varied then due to differing degrees of fiber entanglement. Therefore, an

elongation and tensile absorption energy determination is not a valid representation of what might actually be happening, as elongation and tensile absorption energy are more dependent on the bonding which there was little of--therefore a lack of correlation was found.

Figure 2. Observed Relationship of Tear Factor and Classification Fraction



Figures 3a., 3b., 3c., 3d., 3e.

Distribution Curves of Fiber Lengths

FIGURE 3a. CONTROL SAMPLE

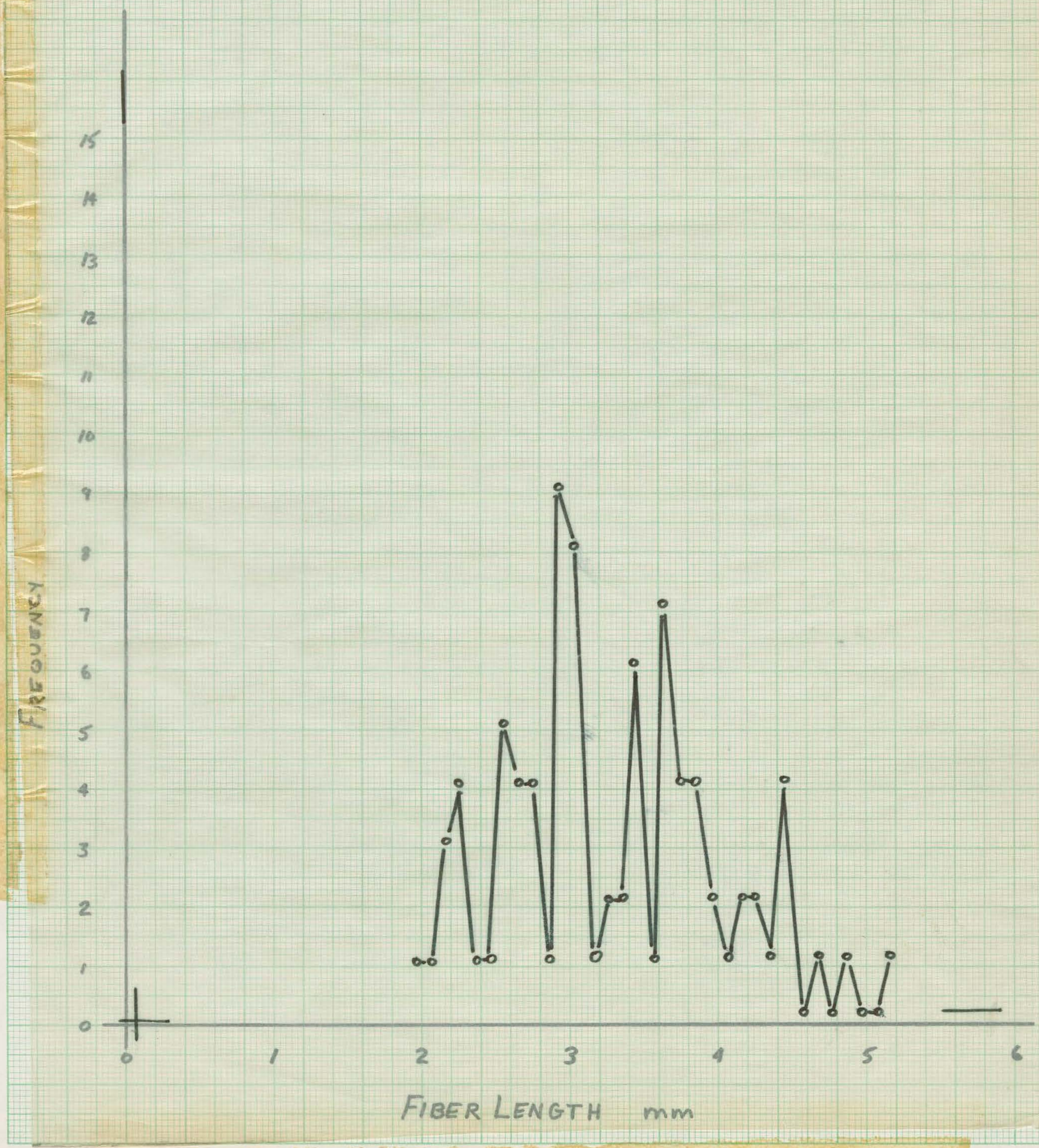


FIGURE 3a. #1 SAMPLE

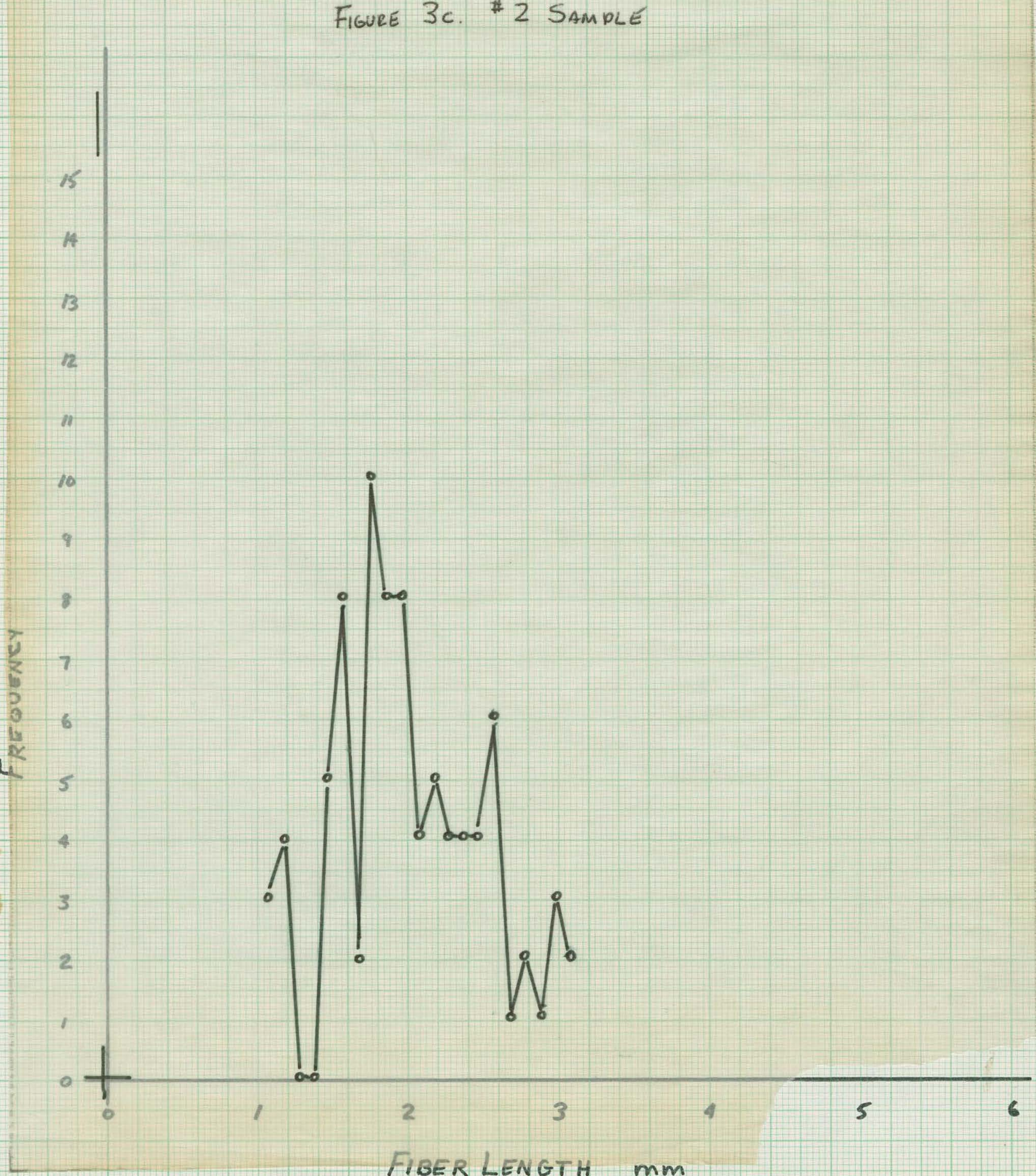


FIGURE 3c. #2 SAMPLE
FREQUENCY
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
FIBER LENGTH mm

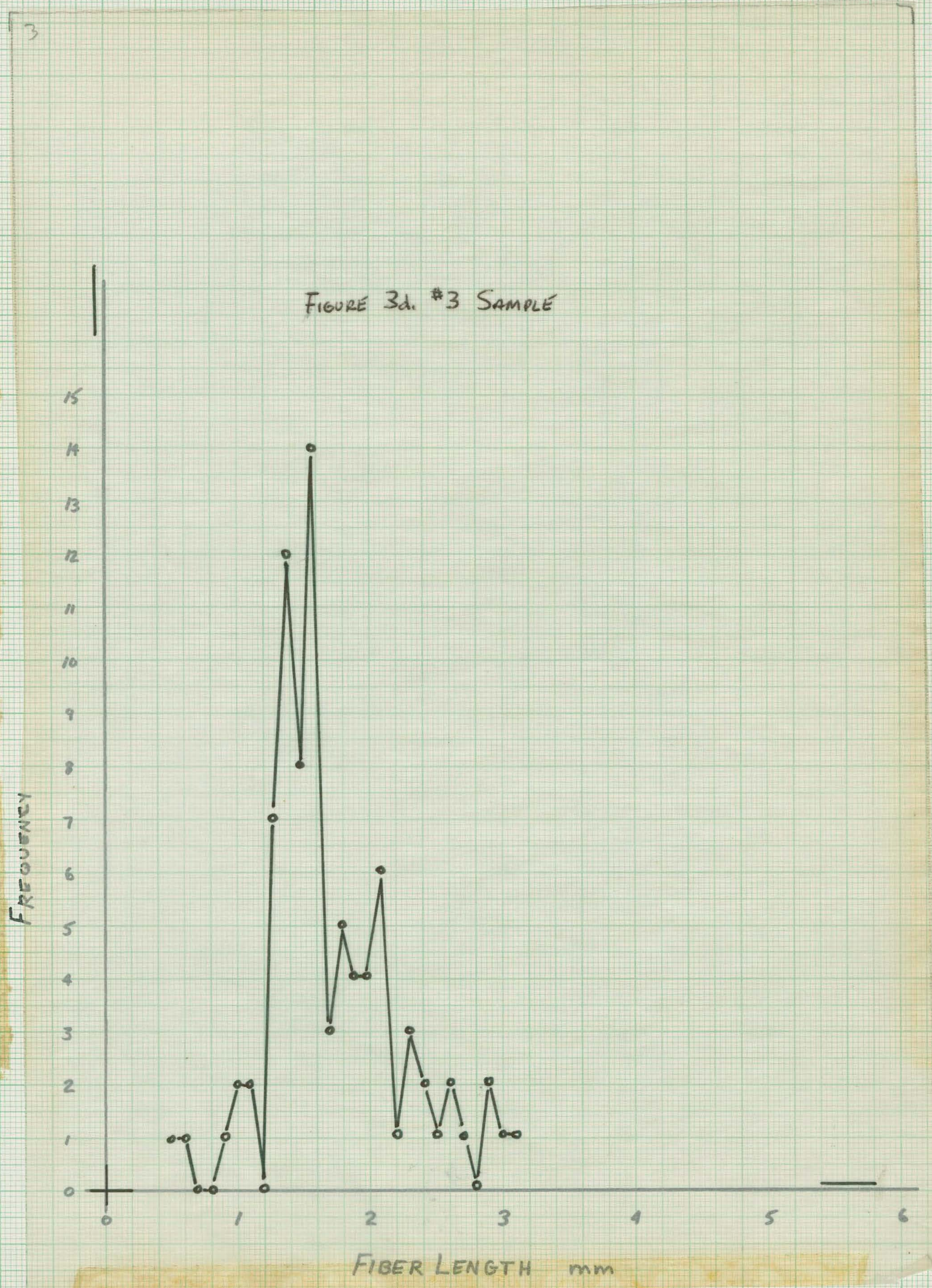


FIGURE 3d. #3 SAMPLE
FREQUENCY
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
FIBER LENGTH mm

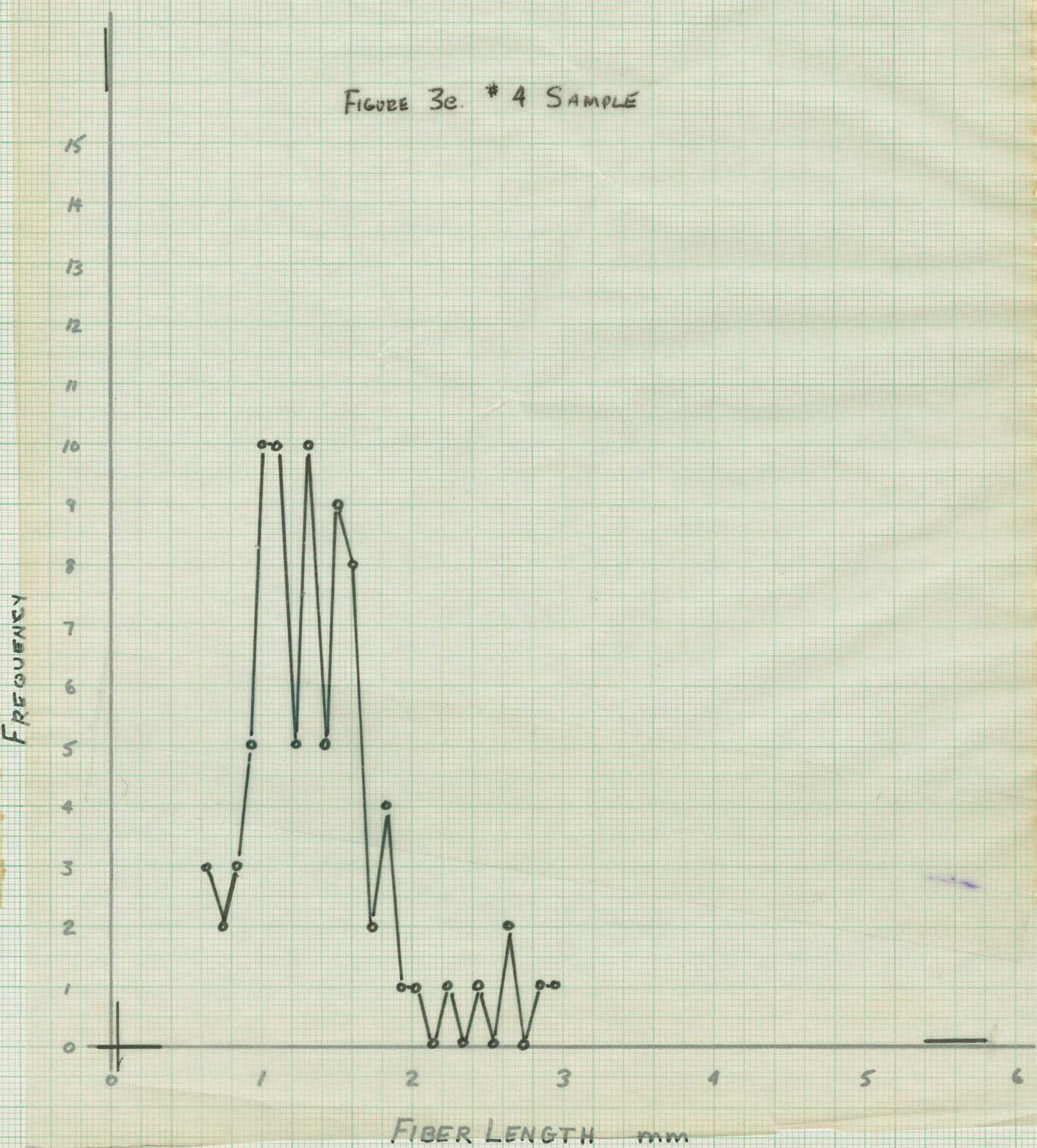


FIGURE 3e. # 4 SAMPLE
FREQUENCY
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
FIBER LENGTH mm

Table I. Tear Test Results

Sample[1]	Ave. Tear Test Results (g)	Tear Factor 100g/r[2]
C	36.7	237
1	20.6	135
2	21.4	135
3	19.0	122
4	12.0	74

[1]C is control sample; 1, 2, 3, 4 are classification fractions
[2]g = grams to tear a single sheet
r = basis weight in grams per square meter, mositure free basis

Table II. Average Fiber Length

Sample	Ave. Fiber Length (mm)	% Decrease[1]
C	3.22	--
1	2.73	15.2
2	2.04	25.3
3	1.74	14.7
4	1.35	22.4

[1]Percent decrease in ave. fiber length from preceeding sample

Table III. Percent Elongation, Average Tensile Load, and Tensile Absorption Energy

Sample	Ave. % Elongation	Ave. Load (kg.)	TAE[1] lb.-in./min.
C	0.65	3.7	0.1298
1	0.68	3.7	0.1378
2	0.71	3.9	0.1645
3	0.67	4.2	0.1705
4	0.64	3.8	0.1547

[1]Tensile Absorption Energy

CONCLUSIONS: Previous investigations into the effect of fiber length on tear strength have been carried out with the presence of a number of variables which could be expected to effect the tear test results. This investigation was carried out with the purpose of eliminating or controlling the variables.

It was found that the distribution of the fiber lengths, as well as the average fiber lengths, have an effect on the tearing strength of the handsheets. The initial drop in the tear factor, from the control sample to the #1 sample, is theorized to be due to a critical value of fiber length and distribution of fiber length in regard to sufficient frictional drag work necessary for strength resulting from the fiber entanglement. Average fiber length cannot be considered alone as effecting the tear strength. Instances were found in which the average fiber length decreased as much as 25.3% from the preceeding sample, while at the same time tear factor did not decrease at all. At other instances average fiber length decreased approximately 15% and was accompanied by a large drop in tear factor. The cause of these results lies in the dependence of the tear factor on the distribution of the fiber lengths from which the handsheets were formed. The distribution curves become important in areas of overlap, when distributions are skewed to one end, and when the distributions are spread out with high frequencies at the ends.

Elongation and tensile absorption energy were found to have no effect on the results of this investigation. The main source of strength for the sheets was from fiber entanglement. As elongation

and tensile absorption energy are more dependent on the bonding of the sheet, which in this investigation was present to only a small degree, no correlation was found between these factors and fiber length.

A check for a correlation between basis weight and elongation was negative. The reasons for this are again traced back to the lack of bonding in the sheets. This does show, however, that the basis weight of the sheets did not systematically effect the elongation study made.

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