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The Affect of Fiber Length on Wet-Web Rheology

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THE AFFECT OF FIBER LENGTH
ON WET-WEB RHEOLOGY

by

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ABSTRACT

A spruce bleached kraft pulp was cut to varying degrees in an attempt to determine the influence of fiber length on the rheological properties of the wet-web. The results indicated that greater fiber lengths increased wet-web strength properties. The rheological data implied surface tension as the basic mechanism of strength properties between 16% and 30% solids, and on this data the mechanism of wet-web behavior under stress was proposed.

TABLE OF CONTENTS

HISTORICAL BACKGROUND

As paper machine speeds have increased in recent years, the problems of wet-end breaks have become a serious matter. Many of the new high speed machines can never operate at their designed speed because these higher speeds promote so many wet-end breaks that it becomes more economical to run at slower speeds. Despite the seriousness of this problem, relatively little work has been done in this field. Many attempts have been made to increase the strength of the wet-web, but in order to solve or minimize this problem, more basic research needs to be done.

To date, practically all the work which has been done in this area, has been either concerned with mechanical aids or groundwood pulp, which in general tends to present the most serious problem. Although groundwood pulps do present the most serious problems of wet-web breaks, higher machine speeds are producing problems in this area even with chemical, and especially hardwood pulps.

All significant work will be presented in the following paragraphs, along with the generally accepted theories.

In considering the causes of wet-end breaks, the first work was started by Brecht in 1936. It was Brecht's contention that, other than machine control, wet-end breaks were due to the tensile strength of the web as it left the couch roll. In his investigation, it was found that there was a linear relationship between solids content (in the range of 8%-23%) and breaking load of the wet-web.

For his purposes he constructed a tensile tester which would measure the breaking loads in the relatively low strength region of wet-webs. The instrument, which is still used today, is basically a zero-span apparatus with horizontal jaws, enabling easy handling of wet-web strips. The strips are formed using a template placed on the wire of a hand-sheet mold. The formed sheet is subsequently couched to the desired solids content, and the individual strips formed by the template are tested and the solids content determined. Using this technique, three to four solids content levels are tested, graphed, and the breaking load at some solids content is interpolated (usually 20% solids) for comparison purposes. To this value, Brecht assigned the term "initial wet-web strength" in order to distinguish it from wet strength paper tests.

In attempts to correlate initial wet-web strength to wet-end breaks, subsequent researchers were relatively unsuccessful for several reasons. One important variable which is not taken into consideration in Brecht's method is the way in which the water is removed. In this test procedure, solids content is obtained by press couching whereas on the machine, solids content is obtained by vacuum couching. The drainage properties of the furnish determine the solids at the couch, and change the "practical" wet-web strength considerably. In addition to differences in solids content, a vacuum-couched sheet has less strength and more bulk than does a press-couched sheet at the same solids level.

In order to obtain a better correlation to wet-web breaks, Andrews (1) and Herwig (4) independently devised testing procedures which would incorporate the drainage or suction couching variable with Brecht's initial wet-web strength. Herwig has developed a procedure which takes into consideration the drainage rate of the pulp over the foils and table rolls, which he calls "drainage effect I", and the air resistance of the wet-web as could be expected at the flat boxes and couch roll, which he calls "drainage effect II". In equation form, he combines initial wet-web strength, drainage effect I, and drainage effect II, which yields a value with a high degree of correlation to wet-end breaks. Along these same lines, Andrews devised a procedure in which a specific volume of air at a set rate was drawn through the sheet as a means of increasing solids content. Although both of these procedures gave better correlation of results to wet-end breaks, it could be concluded that there were other variables to be considered. Some of the other variables were theorized to be angle of take-off, web adhesion to wire, and directionality of the sheet.

Apart from the practicalities of the initial wet-web strength test, several researchers have used it as a tool in the study of strength development of a fibrous web during drying. Being more interested in studying the total range of strength development with increased solids contents to dryness, these researchers had to develop an apparatus having considerable accuracy in the low as well as high strength ranges. In addition, these workers incorporated strain measurements, in order to study the rheological properties of the web from 10% to 95% solids. Although these studies have concentrated mainly on the dryer webs (25% solids and up), the basic theories of wet-web (8%-25% solids) strength have been developed. The main contributions to these theories have been developed by Brecht and Erfurt (2), Lyne and Gallay (6, 7), McCallum (8), and Robertson (9).

According to these sources, the two basic properties which determine wet-web strength are the internal frictional properties of the web, and the surface tension of the suspending or entrained liquid. These mechanisms are revelant in solids ranges up to approximately 25% solids, above which it is theorized that hydrogen bonding is the prevailing strength contributor.

Although the internal frictional properties of the web are defineable only by a series of variables, the surface tension of the resulting effects measured. In general, wet-web strength varies directly with surface tension (2, 6, 7, 8).

The internal frictional properties of the web are not as easily isolated as surface tension effects and for this reason, only superficial studies have been done in this area. Among those properties which have been conjectured or researched are fiber length (1, 2, 4, 5, 9), fiber diameter (6), fiber flexibility (2, 9), fiber swelling (2, 9), fibrillation (2), fines content (1, 2, 4, 5), and electrokinetic properties.

Although several of the properties, such as fines content, fiber diameter, and fiber swelling, have been studied quite extensively, other areas have been left virtually untouched. The most obviously unstudied area is that of fiber length. There has been some work on the addition of longs to groundwood, but no relation between fiber length and wet-web strength have yet been developed.

EXPERIMENTAL DESIGN

In this thesis, an attempt was made to investigate one of these areas of speculation in order to make more complete and sound the theories proposed for wet-web strength.

The area chosen was that of fiber length. The approach taken was to obtain a long fibered pulp (which was bleached spruce kraft) and shorten the fibers by means of a razor blade. By this process, three pulp samples of decreasing fiber length were obtained: the first sample being uncut is referred to as "Long Fiber"; the second pulp, being cut moderately is referred to as "Medium Fiber"; and the third pulp, being cut twice as much as the second pulp, is referred to as "Short Fiber". Because this cutting operation, in addition to shortening fibers, changes the length distribution (the tendency is to decrease the most probable fiber length, and skew the distribution toward the short side), fiber lengths were not determined, but representative pictures were taken of the fibers in order to show visually that fibers were shortened (Figure 5). A picture of several cut fibers is also included, illustrating the clean cuts which were obtained.

The testing of these pulps was accomplished on an Instron Tensile Tester, from which was obtained tensile, elongation, and energy absorption at strip rupture. Because this instrument is based on the principle of constant elongation, together with the fact that a wet-web gradually pulls apart and does not have a point of rupture, a bell shaped stress-strain curve was obtained in testing (Figure 6). The assumption was made that at maximum stress, the structure of the web was destroyed and therefore, this point is considered to be the point of rupture, and the wet-web tensile, elongation, and absorption energy were determined using this stress.

By placing a steel frame or template in the shape of three rectangles on the Noble and Wood sheet mold wire, a wet sheet was formed having three preformed test strips 30 x 90 mm. This sheet was then pressed on a modified Noble and Wood press, after which each strip was tested on the Instron and moisture content determined. The press was modified to produce adjustable pressures, which in turn affected a range of moisture contents for comparison purposes.

RESULTS AND DISCUSSION

All results obtained are available in Tables I, II, III, and IV.

As can be seen in Figure 1, the longer the fiber, the higher is the maximum stress produced by the test strip, through the entire range of solids content tested. A change of slope is apparent at approximately 22% solids, and at this point it is theorized that surface tension effects were at a maximum, after which the fiber-water-air contact areas decreased in area and film thickness, the decreasing area of contacts decreasing strength, and the decreasing film thickness increasing strength at a greater rate.

As for the higher strength of the longer fibers, it can be theorized that as the structure is elongated in the initial stages, the freer ends of the fibers tend to orient themselves in the direction of stress. This paralleling effect increases the linear contact between fibers which in turn increases the area involved in surface tension effects. The point of maximum stress is equivalent to maximum fiber alignment and linear contact. Further elongation of the specimen at this point reduces contact area by pulling pairs or groups of fibers apart and reducing the linear contact area. At this point the observed stress is reduced with further elongation (Figure 6).

With this idea in mind, it is evident that shorter fibers will have a smaller maximum linear contact area at maximum stress and for this reason also have a lower maximum stress.

The same effect is responsible for the greater elongation of the longer fibers at lower solids contents (Figure 2). But at approximately 22% solids, the elongations of all three fiber lengths approach the same value at maximum stress. It can be theorized that at this point, the fibers in linear contact are restricted as to the distance moved across each other while being held together by surface tension forces, because the thinner film of water between the two can only be spread so far before it reaches a maximum at which point the water film breaks-up into several smaller and thicker areas.

The proposed mechanisms are further substantiated if reference is made to the energy absorped by the test specimen in being elongated from the unstressed to maximum stress point (Figure 3). The energy requirement initially increased and reached a maximum at about 22% solids, which was approximately the point of inflection in tensile development as well as the point at which the elongation of all pulps approached equality. Beyond this point, the energy requirement decreases to roughly 30% solids. The drop from 20% to 30% solids indicates the reduced effects of surface tension, as previously proposed. If surface tension had been the only mechanism of sheet strength, the energy curves would have continued to decrease beyond the 30% solids level to a point at which the effective surface water was completely removed and the energy requirement or absorption was zero. Fortunately, this was not the case, and the energy requirement increased beyond 30% solids.

Surface tension effects, although having decreased beyond this point, do contribute to the sheet strength until, as mentioned before, the surface water is practically absent. At the same time another mechanism of sheet strength evidently becomes predominant at 30% solids at a rapidly increasing rate. We assume that this mechanism is hydrogen bonding.

A portion of the "Long Fiber" pulp was soaked, formed into a mat and allowed to air dry at 73^{o} C. and 50% R.H. This pulp was subsequently subjected to the same tests as were the other pulps and is referred to as "Long Fiber (dried)" in Table IV and Figure 4. In general, the tensile, elongation, and energy absorption of the pulp fall mid-way between the "Long Fiber" and "Medium Fiber" pulps in all Figures as can be seen in Table IV. The results indicate several possibilities or combinations thereof which could have caused the lower test results. Upon drying, hornification probably caused a reduction of free fibrils, swelling, and fiber flexibility, which according to the mechanisms proposed would reduce wet-web strengths.

CONCLUSIONS

In summary, the results obtained indicate that, for the pulp used, surface tension effects are responsible for the rheological properties of the wet-web in the 16% to 30% solids content range. The surface tension forces increased within this entire range of solids, although at approximately 22% solids, the liquid film is broken-up by extension of the web, and energy required to rupture the web decreases from this point to approximately 30% solids. The results of tensile, elongation, and energy absorption introduced in the body and Figures of this paper bear this mechanism out. In addition to the specifics evident in the results previously stated, the results also show that the shorter fibers show a point of maximum surface tension effects at a higher solids content than do the longer fibers. This indicates that the shorter the fiber in the structure of the sheet, the more compact is the sheet, enabling fibers to pack more efficiently. Because of this tighter packing and more intimate contact, the water available within the structure was more efficiently used in surface tension effects.

Table I

Long Fiber

Solids Content*	Maximum Stress**	Elongation***	Energy Absorption****
16.4	68	12.3	16.0
16.7	71	15.9	23.3
16.8	71	13.7	16.9
17.0	80	15.1	20.9
17.9	89	13.6	23.4
19.3	123	15.4	34.9
19.6	123	14.8	31.5
21.1	161	14.0	40.5
21.5	167	13.4	40.3
22.5	173	12.0	38.3
23.0	185	11.8	43.7
23.4	187	11.0	35.2
24.3	188	11.1	35.9
24.8	188	10.1	36.2
26.3	198	9.5	35.6
26.6	200	9.4	33.7
28.0	213	8.2	32.1
29.7	229	8.8	38.4
31.7	219	7.9	32.3
35.2	243	7.7	35.8
38.0	271	7.6	36.7
41.6	280	7.4	34.1

Table II

Medium Fiber

Solids Content*	Maximum Stress**	Elongation***	Energy Absorption****
16.7	56	13.2	13.5
17.4	67	14.8	18.6
19.6	103	13.5	28.3
22.2	153	12.9	36.9
23.7	157	11.3	35.0
25.1	174	10.2	31.4
27.0	175	8.9	29.5
30.6	201	7.7	28.4

Table III

Short Fiber

Solids Content*	Maximum Stress**	Elongation***	Energy Absorption****
16.9	43	11.3	10.1
17.4	49	13.0	11.8
19.9	79	11.8	17.4
22.1	114	12.9	27.8
23.7	130	11.2	29.2
25.1	145	10.1	27.6
27.0	151	8.7	26.0
30.2	167	7.8	26.5

Table IV

Long Fiber (Dried)

Solids Content*	Maximum Stress**	Elongation***	Energy Absorption****
16.9	60	13.3	16.1
18.1	78	15.0	22.2
21.0	138	15.3	38.3
22.6	172	11.0	32.4
23.8	178	10.6	34.4
25.1	185	9.6	31.8
34.5	228	7.5	29.9

* Solids Content (%).

** Maximum Stress or Tensile (grams).

*** Elongation (%) to Maximum Stress.

**** Energy Absorbed (10^3 ergs) by sample in elongation to Maximum Stress.

Figure 1

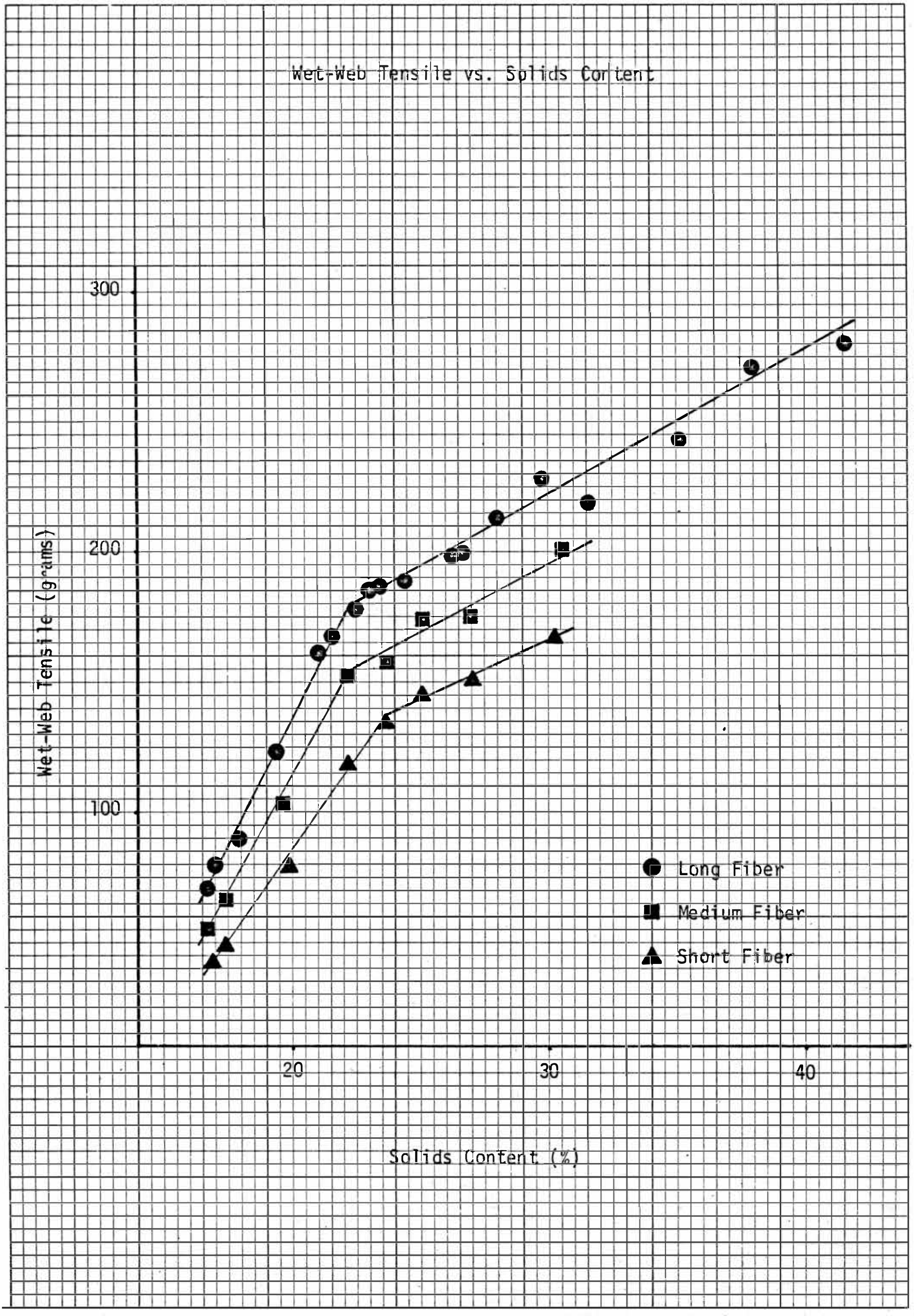

Wet-Web Tensile vs. Solids Content
300
200
100
Wet-Web Tensile (grams)
20
30
40
Solids Content (%)
Long Fiber
Medium Fiber
Short Fiber

Figure 2

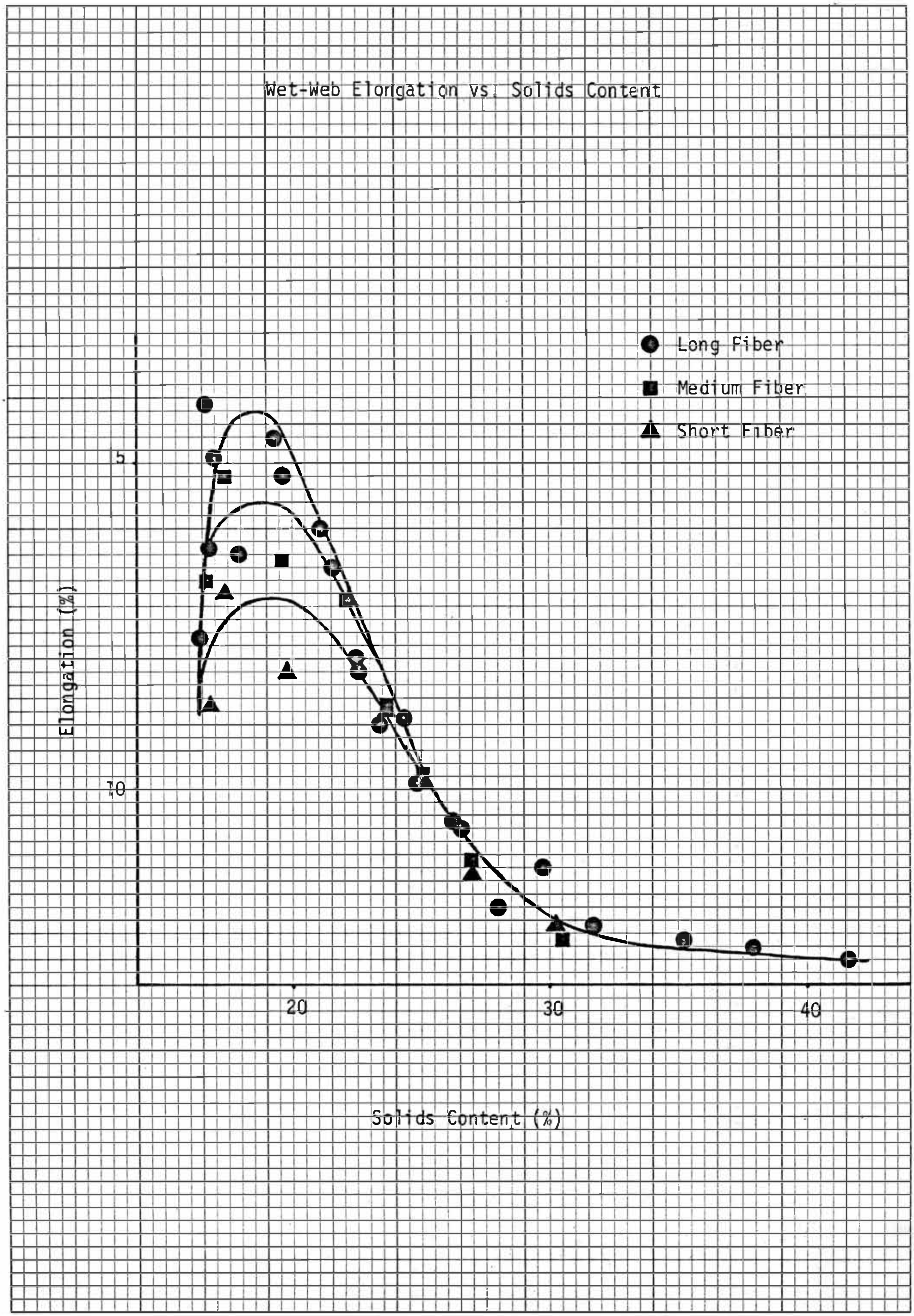

Wet-Web Elongation vs. Solids Content
Long Fiber
Medium Fiber
Short Fiber
Elongation (%)
5
10
20
30
40
Solids Content (%)

Figure 3

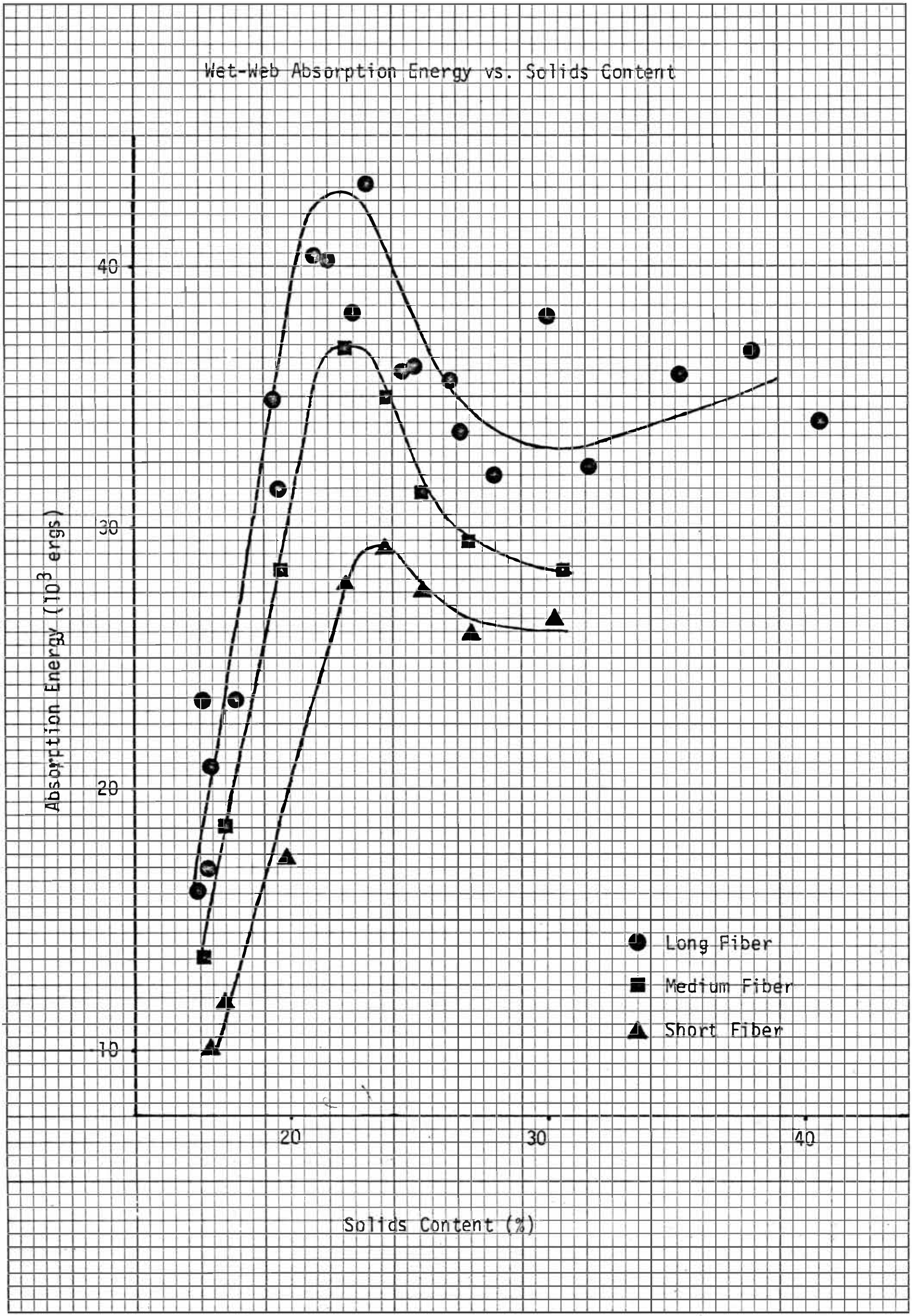

Wet-Web Absorption Energy vs. Solids Content
40
30
20
10
Absorption Energy (10^3 ergs)
20
30
40
Solids Content (%)
Long Fiber
Medium Fiber
Short Fiber

Figure 4

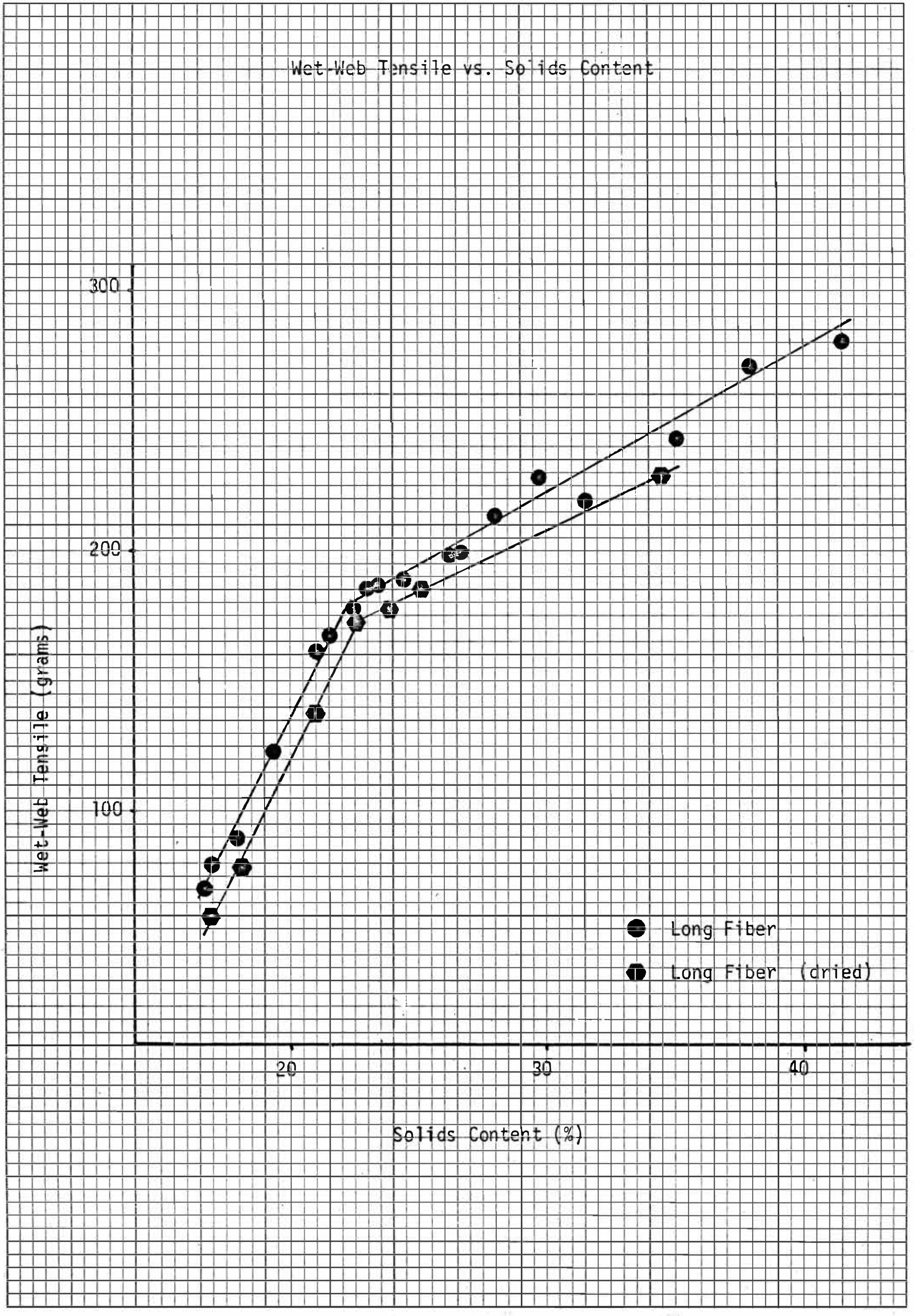
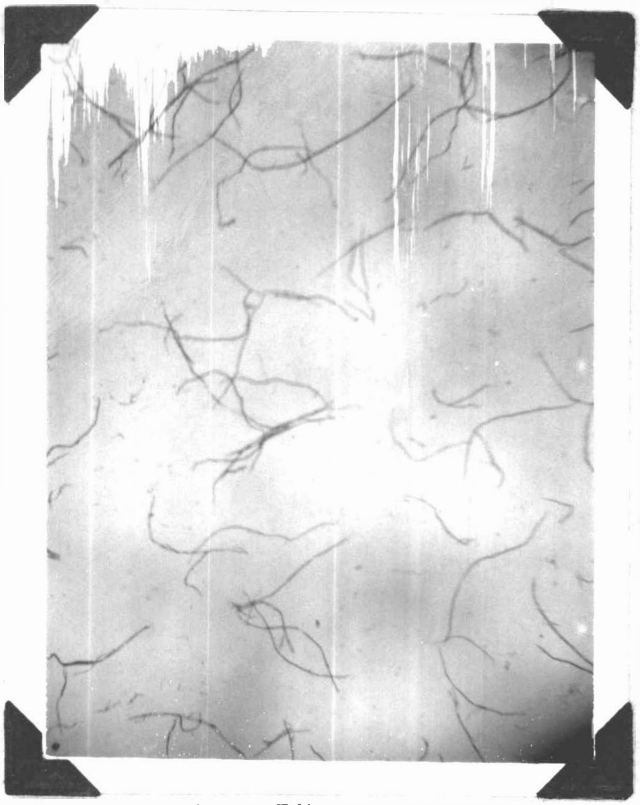
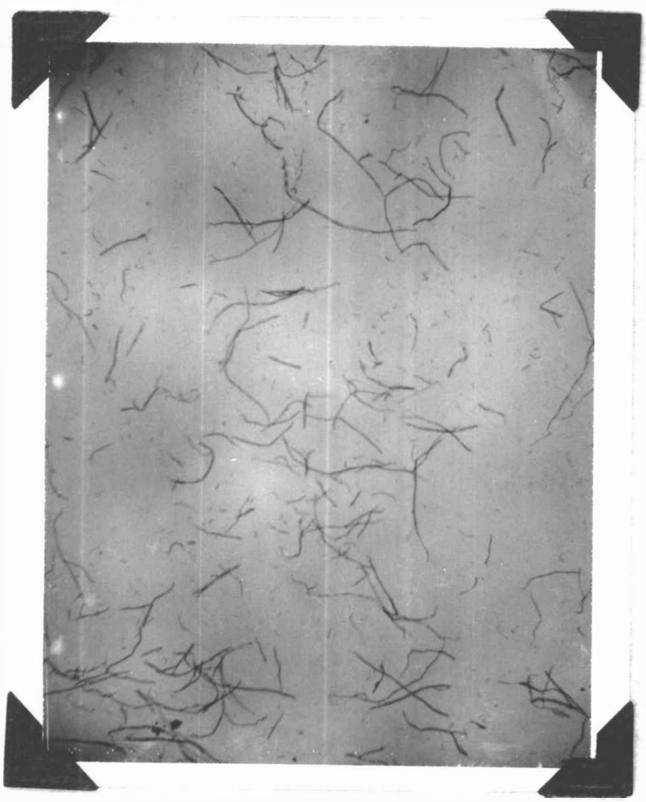

Wet-Web Tensile vs. Solids Content
300
200
100
Wet-Web Tensile (grams)
20
30
40
Solids Content (%)
Long Fiber
Long Fiber (dried)

Figure 5



Long Fiber

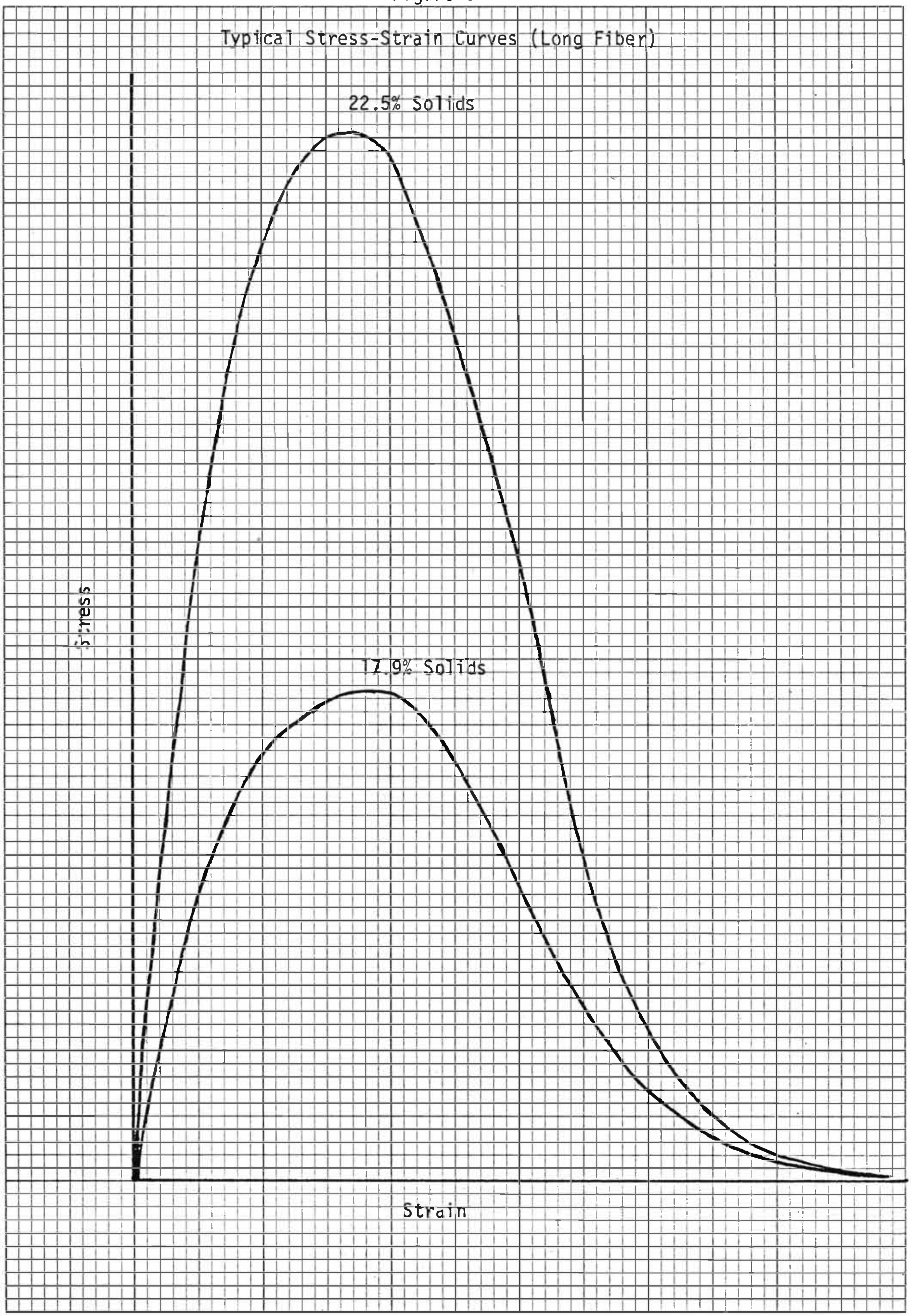
Medium Fiber



Short Fiber

Several Cut Fibers

Figure 6


Typical Stress-Strain Curves (Long Fiber)
22.5% Solids
17.9% Solids
Stress
Strain

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