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Characterizing the Interfiber Bonding of Paper Pulps: Effect of Preparation Pressure on Tensile Test Specimens.

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Polymer Science and Standards Division
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SUMMARY AND CONCLUSIONS

Handsheets in the form of low-density open webs of grammage 2.5 g/m^2 were prepared from Northern and Southern softwood kraft pulps, unbeaten and beaten for 5000 revolutions in a PFI laboratory beater. These webs were formed on filter paper and pressed for five minutes against a ferrotype backing plate. Webs were prepared at pressures of 44 kPa (6.4 lb/in^2), 350 kPa (51.2 lb/in^2) and 660 kPa (96 lb/in^2).

Specimens selected from these handsheets were tested to the breaking point in a tensile tester. The resulting force-elongation curves were analyzed to obtain a characteristic energy E_1 interpreted as the average energy lost per interfiber bond break by fibers in the vicinity of the break. The average initial percent elongation per bond break was also determined for each handsheet. These two parameters are used to characterize the relative strength of the interfiber bonds in the web. The objective of this work was to determine if values of the parameters obgained were dependent on the pressure used in the preparation of the webs.

Handsheets formed from the beaten pulps were coherent and well bonded. It was found that for the beaten Northern pulp webs, the value of E_1 and the initial elongation per break obtained were independent of the pressure used during preparation. The corresponding values of these parameters for beaten Southern pulp webs were also independent of preparation pressure. However there was evidnece that the Southern pulp web prepared at 660 kPa pressure was of slightly inferior quality. It may have been damaged when it was peeled from the ferrotype backing plate after pressing.

The handsheets formed from the unbeaten Northern and Southern pulps were weak and flimsy. Values of the parameters obtained for the Northern pulp webs were not dependent on preparation pressure. Values of E_1 for the unbeaten Southern

pulp webs were not dependent on pressure, but values of initial elongation per break for the webs prepared at 330 kPa and 660 kPa were excessively large, indicating that these webs had a very loose structure. Presumably these webs, possessing intrinsically weak bonding, were easily damaged by removal from the ferrotype backing plate.

In general it seems that the quality of bonding between fibers in these handsheets is not affected by preparation pressure between 44 kPa and 660 kPa. However webs which are weakly bonded intrinsically may stick to the backing plate at preparation pressures of the order of 350 kPa and may be damaged upon subsequent removal.

INTRODUCTION

If a specimen from a handsheet of pulp fibers formed into a low-density open web is elongated to break in a sensitive tensile tester, a force-elongation curve containing numerous jags is obtained. Each jag is caused by the breakage of a bond between fibers constituting the handsheet network. Data for a curve of work of extension versus number of bond breaks can be obtained by integrating under the force-elongation curve and counting the discontinuities in slope caused by the bond breaks. A characteristic energy E, interpreted as the average stored energy lost per break by fibers in the vicinity of the broken bond, can be determined from this curve. This energy is used as a measure of the bond adhesion between two fibers.

From the force-elongation data a curve of percent elongation of the specimen versus number of bond breaks can also be plotted. The initial slope of this curve, or initial percent elongation of the specimen per break, is a measure of the tightness of the web structure, or density of bonds per unit area of web.

Relative bond adhesion and web tightness have been measured on handsheet webs prepared from Northern and Southern softwood kraft pulps, unbeaten and subjected to various amounts of beating. Details of this work have been given in the two previous reports [1,2].

In the previous work experiments were carried out on webs prepared by two different methods. In the first method cotton linters pulpsheet was used as a forming medium, and the web was pressed against a ferrotype plate at 660 kPa (96 lb/in^2) for 5 minutes. In the second method filter paper was used as a forming medium, and the web was pressed against a ferrotype plate at 44 kPa (6.4 lb/in^2) for 5 minutes.

Handsheets were easier to prepare by the second method, and appeared to be well bonded and uniform in texture. However the curves of work of extension versus number of bond breaks obtained by tests on these handsheets had a scalloped appearance with many changes in slope. As a rule the minimum slopes that occurred extended over only a few bond breaks so the values of these slopes were uncertain. It was not possible to obtain a good estimate of E by averaging these minimum slope values. This difficulty was not so prevalent in the webs formed at higher pressures by the first method.

It is important to know if forming pressures affect the test results so that a procedure for preparing standard handsheets can be established. A low forming pressure would be desirable in order that the web can be peeled easily from the forming medium and the ferrotype backing plate. This report therefore gives the results of tests on webs formed at several different pressures.

EXPERIMENTAL

Handsheets of 2.5 g/m^2 mass per unit area were prepared from Northern and Southern softwood kraft pulps used previously [1,2]. The pulps were unbeaten and beaten for 5000 revolutions in a PFI laboratory beater. The method of preparation was the same as that reported previously. Filter paper was used as the forming medium. Pressing in a hydraulic press was carried out at room temperature for five minutes.

The following handsheets were prepared from unbeaten pulps:

1. Northern pulp, pressed at 350 kPa (51.2 lb/in^2)
2. Northern pulp, pressed at 660 kPa (96 lb/in^2)
3. Southern pulp, pressed at 350 kPa (51.2 lb/in^2)
4. Southern pulp, pressed at 660 kPa (96 lb/in^2).

The following handsheets were prepared from pulp beaten for 5000 revolutions:

5. Northern pulp, pressed at 44 kPa (6.4 lb/in^2)
6. Northern pulp, pressed at 350 kPa (51.2 lb/in^2)
7. Northern pulp, pressed at 660 kPa (96 lb/in^2)
8. Southern pulp, pressed at 44 kPa (6.4 lb/in^2)
9. Southern pulp, pressed at 350 kPa (51.2 lb/in^2)
10. Southern pulp, pressed at 660 kPa (96 lb/in^2).

The procedure for preparing, mounting and testing of the specimens from the handsheets was unchanged. Specimen dimensions were 1 cm width by 2 cm length. The specimens were tested at a crosshead speed of 0.2 cm/min and a chart speed of 20 cm/min. Load cell sensitivities ranged between 0.02 N (2 g) full scale for handsheets of unbeaten pulp and 0.2 N (20 g) full scale for handsheets of beaten pulp.

ANALYSIS OF THE DATA

Figure 1 provides an illustrative example of the force-elongation curve obtained by testing one of the web specimens, in this instance specimen number 12 from the handsheet of beaten Southern pulp pressed at 44 kPa. Figure 2 is the corresponding plot of work of elongation versus number of bond breaks, and figure 3 the plot of percent elongation versus number of bond breaks.

According to the argument used in a previous report [1], energy is stored in the web during the elongation process, and some of the store of energy is dissipated when a bond between fibers breaks. In order to estimate the average energy dissipated per bond break it is necessary to make some assumptions about the relationship between the force sustained by a network and the energy stored in it.

There is a functional relationship between the stored energy and the force sustained by the web. In an extension process in which none of the interfiber bonds are broken this relationship could be found by integrating under the force-elongation curve to obtain data on work of extension versus force. During the extension, part of the work done would be dissipated by the friction involved in aligning fiber segments, but if the extension were removed and the web specimen then re-extended, the frictional dissipation would not recur and the work of extension would all be stored as energy in the network.

The analysis to follow is based on the assumption that the force resisting extension of a web is sustained by only a small fraction of the fiber segments between bonds. It follows from this assumption that in many instances the force-energy relationship can be regarded as unchanged by a bond break. To see this consider a typical web in which the fiber segments between bonds have all possible orientations. It seems reasonable to assume that when the web is extended most of the resisting force will be borne by those relatively few fiber segments that are straightest and best aligned in the direction of extension. There is a redundancy of unloaded fiber segments. Most of these segments bear little or no load, because they are unaligned, or because most of the load is borne by adjacent fibers with shorter straighter segments between bonds. When a bond breaks leaving a small or moderate-size hole in the network other fibers in the vicinity of the break assume the load relinquished by the broken bond. Thus the web can be expected to behave as though the force overall were sustained by the same number of load bearing elements before and after the break. The force-energy relationship therefore should be the same except for very small changes due to improved alignment of the load bearing segments.

If the web structure has changed significantly as the result of many bond breaks, or has incurred significant damage such that portions of the web are torn away and can no longer store energy, the force-energy relationship applying in this case will differ from the relationship applying in an earlier stage of the extension. However if the load bearing portions of the changed web still retain a large fraction of unoriented unstressed segments between bonds, the force-energy relationship should still remain essentially the same over a subsequent series of bond breaks that result in small or moderate-size holes. It follows from these assumptions that, if in a series of breaks the forces after break drop to approximately the same level, the total energy stored in the web just after each of two successive breaks is the same, and the energy dissipated during the second break is equal to the increment of energy stored during the transition between the two breaks.

Figure 2 is a plot of cumulative work of extension versus number of bond breaks. The slope of this plot between successive breaks thus is equal to the work of extension per bond break. In many instances when a bond breaks the force after break is greater than the force after the previous break. In such a case the slope of the plot, figure 2, has a high value, because only part of the work done is dissipated during the second break, the rest is stored as strain energy in the network. When in a series of two or more breaks the forces after break return to approximately the same level, the work done per break is equal to the energy dissipated per break. In these cases the slopes of the plot, figure 2, have a lower value. These slopes have been indicated by the short line segments drawn in the figure. Slopes of lower value however can also occur when the force after a break is less than that after a previous break. If such is the case, as determined from the original data of figure 1, it is necessary to exclude these slopes from consideration.

The average energy dissipated per break, E, is estimated as the average slope of the line segments such as those sketched in figure 2. This graphical procedure is the one that was used to analyze data of the previous two reports. Results given in the first report [1] were obtained from tests on handsheets prepared by the first method using cotton linters pulpsheet as a forming medium and pressing at 660 kPa. Curves of work of extension versus number of breaks had relatively few regions of low slope but of much longer duration, so that fairly reliable estimates of E could be made. Results given in the second report [2] were obtained from tests on handsheets prepared by the second method using a filter paper forming medium and pressing at 44 kPa. Curves of work of extension versus number of breaks were similar to figure 2, and estimates of E obtained from these curves were less reliable than those of the first report.

Obtaining values of E by the graphical method just described is a tedious and highly subjective process. Although some of the results reported here were obtained in this way, most of the results were computed directly by another method which is more objective and avoids curve plotting. These computed values of average energy dissipation per break are designated by the symbol E_1.

In the force-elongation curve, figure 1, drops in force resulting from bond breaks are distributed through a wide range of values. The small drops presumably represent breaks in which the network is left essentially intact; i.e., other fibers in the vicinity assume the load relinquished by the fibers involved in the break. Large drops presumably represent breaks in which the network incurs significant damage.such as a large hole or torn portions. By considering only those force drops equal to or less than an arbitrary value D, attention can be focussed on those breaks resulting in damage sufficiently slight that the same force-energy relationship applies before and after the break.

Figure 4 depicts two "jags" in a force-elongation curve that are suitable for calculating the energy parameter E_1. In the two diagrams point 0 designates the force and elongation values prevailing just after a bond break. As the specimen is elongated the force increases up to its value at point 1, where the next break occurs and the force drops to point 2. (Elongation e_2 is greater than elongation e_1 because the specimen is being elongated at a constant rate and the drop in force occurs over a finite time). Elongation e_3 is the elongation attained during the extension, at which a force equal to the force after break F_2 is attained. Presumably the energy stored in the network at elongation e_3 is the same as the energy remaining in the network after the break at elongation e_2. The quantity D shown in the figure represents the maximum force drop used in the calculation of energy dissipation.

Only selected regions of the force-elongation curve are used in the calculations. Situations in which the force drop $F_1 - F_2$ exceeds D or situations in which the force after break is less than a certain minimum value H are excluded because of the possibility that the network may have been excessively damaged. Situations in which the force drop

$F_2 - F_1$ is less than 0.1D or in which the force rise $F_1 - F_0$ is less than 0.2D are also excluded. These cases in which the change in force is not well defined represent situations in which the processes occurring in the network are not well understood. Thus only the two situations depicted in figure 4 are used in the calculation. In situation a the energy dissipation is taken as the area under the force-elongation curve between points 0 and 2, and in situation b as the area between points 3 and 2. The energy dissipations calculated in this way from a given force-elongation curve are averaged to obtain the value of E_1. A computer program was devised to perform these calculations.

The curve of percent elongation versus number of breaks, figure 3, shows that the initial portion is essentially linear over a large range, except for the first five points. This behavior was true in general for the specimens of handsheets prepared from the beaten pulps. Some of the results reported here were obtained graphically from plots similar to the one shown in figure 3, but in order to eliminate the necessity for these plots, a computer program was devised that provided a least squares fit to those elongation points ranging between a minimum break (MINBK) and a maximum break (MAXBK). The value of MINBK was usually 5. The value of MAXBK was usually 50, but could be less depending on the total number of bond breaks incurred by the specimen in tearing completely apart.

RESULTS AND DISCUSSION

Specimens of handsheets formed from beaten Northern pulp pressed at 44 kPa and at 350 kPa were tested. The data were analyzed graphically, and the results are given in tables 1 and 2. Values of average energy dissipation per break E and initial percent elongation per break for the two handsheet samples are the same, indicating that these mechanical properties were not affected by forming pressure. Results of similar tests on beaten Southern pulp handsheets are given in tables 3 and 4. Again the values of E and of initial percent elongation per break for these samples are the same, indicating that these mechanical properties do not depend on forming pressure.

Tables 5, 6 and 7 present the results of tests on handsheets of beaten Northern pulp pressed at 44 kPa, 350 kPa and 660 kPa respectively. The tests listed in table 5 are the same as those in table 1, but the values of E_1 and of the initial elongation per break were obtained by a computer program. Similarly the tests of table 6 are the same as those of table 2.

In tables 5, 6 and 7 the value of E_1 given for each specimen is the average of the energy dissipations calculated for each of a number of situations such as those depicted in figure 4. The number used in each average is given in the column headed "Number of breaks" . For instance in table 5 E_1 for specimen number 1 is the average of dissipations calculated from 18 situations. The average of the E_1's given in each table is the unweighted average of the E_1 values tabulated for the different specimens. The standard deviation is calculated from the deviations of the specimen E_1's from this average. This particular method of averaging is thus the same as that used to calculate the average E's given in tables 1 and 2. Computer analysis values of the average energy dissipation per break and the initial percent elongation per break for the beaten Northern pulp handsheets of tables 5, 6 and 7 appear to be independent of forming pressure.

The results of all the tests on beaten Northern pulp handsheets are summarized in table 11. For completeness this summary table includes results reported previously [2] for a beaten Northern pulp handsheet pressed at 44 kPa. The value of E (obtained graphically) by measurements on this different handsheet has a somewhat lower value than the value given in table 1. Sample to sample variation may account for some of this discrepancy but most of it should be attributed to subjectivity of the graphical measurement process.

Tables 8, 9 and 10 present results of tests on handsheets of beaten Southern pulp pressed at 44 kPa, 350 kPa and 660 kPa respectively. The values of E_1 and initial percent elongation per break given were obtained by a computer program. The tests in table 8 are the same as those in table 3, ant the tests of table 9 are the same as those of table 4.

Computer analysis of tests on beaten Southern pulp handsheets pressed at 44 kPa and 350 kPa (tables 8, 9) gives values of E_1 and initial elongation per break which are independent of the forming pressure, as does the graphical analysis of tests on these handsheets (tables 3, 4). The average values of E_1 and initial elongation per break for the handsheet pressed at 660 kPa (table 10) are both higher than the values obtained for the handsheets formed at the lower pressures, but the standard deviations are also larger. The higher forming pressure probably has not directly affected the E_1 and elongation values, but has affected the uniformity and consistency of the test results. The higher more erratic value (0.217 ± 0.044 %/break) for the initial elongation per break suggests that some of the test specimens had a looser network texture in which some of the fiber crossings were not bonded. This may be attributed to damage incurred by the handsheet when it was separated from the ferrotype backing plate after pressing. The results on beaten Southern pulp handsheets are summarized in table 12. For completeness table 12 also includes results reported previously [2] on a different beaten Southern pulp handsheet pressed at 44 kPa.

In table 11 listing results for the beaten Northern pulp handsheets the average values of energy dissipation per break E (tables 1, 2) obtained by graphical analysis are close to the values of E_1 obtained by computer analysis. This correspondence in value must be regarded as somewhat fortuitous, as the E_1 value obtained depends on the parameters D and H chosen for the computer calculation. This same correspondence of E and E_1 values is also noted in the results for beaten Southern pulp handsheets (table 12), and must also be regarded as somewhat fortuitous.

The results listed in tables 11 and 12 also confirm results reported previously. The initial elongation per break for the beaten Southern pulp handsheets is larger than that for the beaten Northern pulp handsheets. This is interpreted to mean that the beaten Southern pulp web has a looser more open texture. This interpretation seems reasonable because it is known that the Southern pulp fibers are coarser than the fibers of Northern pulp. Thus although the beaten Northern and Southern pulp handsheets have the same mass per unit area, the Southern pulp web comprises fewer fibers per unit area.

According to the results of tables 11 and 12 the average energy dissipation per break is the same for the beaten Northern and Southern pulp handsheets. This equality of E or E_1 values, which has been reported previously, does not necessarily mean that the strength of bonding between the Northern pulp fibers is the same as that between the Southern pulp fibers. The values obtained for E or E_1 may depend upon the mesh size of the network, and in this instance the Southern pulp network, as noted above, has the larger mesh size. The effect of mesh size is not known at present, but it is planned to investigate it in some future work.

Handsheets formed from unbeaten pulps were weak and flimsy, especially those formed from the unbeaten Southern pulp. As an example figure 5 is the force-elongation curve obtained in the test of specimen number 11 from the handsheet of unbeaten Southern pulp pressed at 660 kPa. Throughout the course of the elongation the force never exceeds a value of 2.0 mN (0.2 g), and the specimen is torn completely apart after approximately 25 bond breaks. The breaking of this specimen is also characterized by relatively large elongations between breaks, as compared to the elongations per break observed when specimens from beaten pulp handsheets are tested. Force-elongation curves that resulted from tests on each of the unbeaten pulp handsheets were similar to figure 5.

Inasmuch as many specimens obtained from the unbeaten pulp handsheets had a very loose texture it would seem that the force sustained by the network was channeled through relatively few effective bonds. Thus the assumption that the force-energy relationship remains the same over a series of breaks might not be valid on this account. However in figure 5 it should be noted that the slopes of this curve in the intervals between breaks are all approximately the same. Similar behavior was noted in the force-elongation curves for the other specimens. This implies that the force-energy relationship does remain constant, so that a value of E_1 can be calculated. The calculated values of E_1, and of the initial elongation per break, that were obtained however were not very consistent or reliable, but are presented here notwithstanding, as they provide some useful information.

Results from tests on unbeaten Northern pulp handsheets are presented in tables 13 and 14. These results were obtained by a computer analysis of the force-elongation curves. Average values of E_1 and the initial elongation per break for the two handsheets, one pressed at 350 kPa and the other at 660 kPa, are approximately the same, but the standard deviations particularly for the initial elongation per break values are large.

A summary of results is given in table 17, where data on a handsheet pressed at 44 kPa from a previous report [2] (analyzed graphically) is also included. The summarized results do not indicate that there is any systematic effect of forming pressure on the values of E_1 (or E) and the elongation per break for these handsheets of unbeaten Northern pulp.

Computer analyzed data from tests on unbeaten Southern pulp handsheets are presented in tables 15 and 16 and summary table 18. The summary table includes previously reported [2] results (obtained graphically) for a handsheet pressed at 44 kPa. According to these results the handsheets pressed at 330 kPa and 660 kPa are of inferior quality. The initial elongation values obtained for these handsheets are excessively large and have very large specimen-to specimen variation, suggesting a very loose and flimsy network structure. When these handsheets were prepared, it was difficult to separate them from the ferrotype backing plate, and it is probable that they were damaged in the process.

REFERENCES

1. J.C. Smith and E.L. Graminski, Characterizing the Interfiber Bond Strengths of Paper Pulps in Terms of a Breaking Energy, Progress report covering the period January 1, 1976 to June 30, 1976, NBSIR 76 - 1148. Available from National Technical Information Service PB 264,689.
2. J.C. Smith and E.L. Graminski, Characterizing the Interfiber Bond Strength of Paper Pulps in Terms of a Breaking Energy, Progress report covering the period July 1, 1976 through September 30, 1976, NBSIR 77 - 1286. Available from National Technical Information Service PB 276,473.

Table 1.
Graphical Analysis of Tests on Beaten Northern Pulp Handsheets Pressed at 44 kPa

Specimen	E 10^{-7} J/break	Init. elong. per break %/break
1	4.32	0.128
2	6.48	0.145
5	4.10	0.124
6	5.17	0.127
7	4.80	0.186

Average ± standard deviation

E $(4.97 \pm 0.94)\text{x}10^{-7}$ J/break

Initial elongation per break 0.142 ± 0.026 %/break

Table 2.
Graphical Analysis of Tests on Beaten Northern Pulp Handsheets Pressed at 350 kPa

Specimen	E 10^{-7} J/break	Init. elong. per break %/break
1	5.20	0.144
2	4.88	0.130
3	5.00	0.137
4	4.60	0.144
7	5.00	0.126

Average ± standard deviation

E $(4.94 \pm 0.22)\text{x}10^{-7}$ J/break

Initial elongation per break 0.136 ± 0.008 %/break

Table 3.

Graphical Analysis of Tests on

Beaten Southern Pulp Handsheets Pressed at 44 kPa

Specimen	E 10^{-7} J/break	Init. elong. per break %/break
2	4.50	0.200
3	4.80	0.192
4	5.36	0.190
7	5.30	0.184
12	5.00	0.155

Average ± standard deviation

E $(4.99 \pm 0.36)\text{x}10^{-7}$ J/break

Initial elongation per break 0.184 ± 0.017 %/break

Table 4.

Graphical Analysis of Tests on

Beaten Southern Pulp Handsheets Pressed at 350 kPa

Specimen	E 10^{-7} J/break	Init. elong. per break %/break
2	5.60	0.198
4	5.40	0.174
5	4.76	0.162
6	5.10	0.185
11	5.60	0.180

Average ± standard deviation

E $(5.29 \pm 0.36)\text{x}10^{-7}$ J/break

Initial elongation per break 0.180 ± 0.013 %/break

Table 5.
Computer Analysis of Tests on
Beaten Northern Pulp Handsheets Pressed at 44 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
1	5.58 ± 2.87	18	0.123
2	5.41 ± 2.08	21	0.144
5	6.64 ± 4.18	20	0.134
6	4.76 ± 2.47	18	0.141
7	3.13 ± 0.82	13	0.195

Average ± standard deviation

E_1 $(5.10 \pm 1.29)\times10^{-7}$ J/break

Initial elongation per break 0.147 ± 0.028 %/break

Table 6.
Computer Analysis of Tests on
Beaten Northern Pulp Handsheets Pressed at 350 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
1	5.11 ± 2.30	27	0.135
2	6.55 ± 3.37	28	0.138
3	4.28 ± 2.12	42	0.125
4	6.08 ± 2.95	25	0.141
7	4.91 ± 2.06	21	0.127

Average ± standard deviation

E_1 $(5.39 \pm 0.92)\times10^{-7}$ J/break

Initial elongation per break 0.133 ± 0.007 %/break

Table 7.
Computer Analysis of Tests on Beaten Northern Pulp Handsheets Pressed at 660 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
1	5.22 ± 2.38	23	0.149
2	4.95 ± 2.28	14	0.151
3	5.39 ± 2.72	23	0.159
4	4.99 ± 1.96	32	0.140
5	5.20 ± 2.46	24	0.119

Average ± standard deviation

E_1 $(5.15 \pm 0.18)\times10^{-7}$ J/break

Initial elongation per break 0.144 ± 0.016 %/break

Supplementary Information - Tables 5, 6, 7.

For computation of E_1:

Maximum force drop D 0.981 mN (0.1 g)

Minimum force H 9.81 mN (1.0 g)

Average E_1 is unweighted average of E_1 values for each specimen.

Initial elongation per break:

Values of initial elongation per break were obtained by a least squares fit of data points ranging from a minimum break (MINBK) of 5 through a maximum break (MAXBK) of 50.

Table 8.

Computer Analysis of Tests on

Beaten Southern Pulp Handsheets Pressed at 44 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
2	4.66 ± 2.08	20	0.188
3	4.41 ± 1.49	52	0.172
4	4.99 ± 2.17	22	0.181
7	4.64 ± 0.96	11	0.186
12	4.32 ± 1.94	37	0.151

Average ± standard deviation

E_1 (4.60 ± 0.26)x10^{-7} J/break

Initial elongation per break 0.176 ± 0.015 %/break

Table 9.

Computer Analysis of Tests on

Beaten Southern Pulp Handsheets Pressed at 350 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
2	4.81 ± 2.21	22	0.208 1/
4	4.87 ± 1.95	22	0.179
5	3.65 ± 1.07	11	0.149
6	4.65 ± 1.51	21	0.222
11	4.30 ± 1.86	36	0.179 2/

Average ± standard deviation

E_1 (4.46 ± 0.50)x10^{-7} J/break

Initial elongation per break 0.187 ± 0.028 %/break

Table 10.
Computer Analysis of Tests on
Beaten Southern Pulp Handsheets Pressed at 660 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break
1	5.71 ± 2.35	20	0.185
2	5.04 ± 1.89	31	0.252
3	7.07 ± 2.44	26	0.179
4	4.57 ± 1.95	13	0.196
5	4.84 ± 2.04	17	0.276

Average ± standard deviation

E_1 $(5.45 \pm 1.00) \times 10^{-7}$ J/break

Initial elongation per break 0.217 ± 0.044 %/break

Supplementary Information - Tables 8, 9, 10.

For computation of E_1:

Maximum force drop D 0.981 mN (0.1 g)

Minimum force H 9.81 mN (1.0 g)

Average E_1 is unweighted average of E_1 values for each specimen.

Initial elongation per break:

Values of initial elongation per break were obtained by a least squares fit of data points ranging from a minimum break (MINBK) of 5 through a maximum break (MAXBK) of 50, except where noted.

1. MINBK 10, MAXBK 100
2. MINBK 5, MAXBK 100

Table 11.

Summary of Results for Beaten Northern Pulp Handsheets

Identification	Forming pressure kPa	E or E_1 ± std. dev. 10^{-7} J/break	Init. elong. per break %/break
Graph [1]	44	3.36 ± 0.79	0.133 ± 0.022
Table 1 (graph)	44	4.97 ± 0.94	0.142 ± 0.026
Table 2 (graph)	350	4.94 ± 0.22	0.136 ± 0.008
Table 5 (comp.)	44	5.10 ± 1.29	0.147 ± 0.028
Table 6 (comp.)	350	5.39 ± 0.92	0.133 ± 0.007
Table 7 (comp.)	660	5.15 ± 0.18	0.144 ± 0.016

Table 12.

Summary of Results for Beaten Southern Pulp Handsheets

Identification	Forming pressure kPa	E or E_1 ± std. dev. 10^{-7} J/break	Init. elong. per break %/break
Graph [1]	44	4.09 ± 0.53	0.160 ± 0.023
Table 3 (graph)	44	4.99 ± 0.36	0.184 ± 0.017
Table 4 (graph)	350	5.29 ± 0.36	0.180 ± 0.013
Table 8 (comp.)	44	4.60 ± 0.26	0.176 ± 0.015
Table 9 (comp.)	350	4.46 ± 0.50	0.187 ± 0.028
Table 10 (comp.)	660	5.45 ± 1.00	0.217 ± 0.044

[1] From previous report [2].

Table 13.

Tests on Unbeaten Northern Pulp Handsheets Pressed at 350 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break	MINBK, MAXBK
3	0.94 ± 0.46	15	0.331	10,40
5	1.13 ± 0.46	26	0.194	5,50
7	1.08 ± 0.45	25	0.162	5,40
8	0.92 ± 0.30	19	0.149	5,50
10	1.13 ± 0.44	12	0.213	5,50

Average ± standard deviation

E_1 $(1.04 \pm 0.10)\times10^{-7}$ J/break

Initial elongation per break 0.210 ± 0.072 %/break

Table 14.

Tests on Unbeaten Northern Pulp Handsheets Pressed at 660 kPa

Specimen	E_1 10^{-7} J/break	Number of breaks	Init. elong. per break %/break	MINBK, MAXBK
2	0.88 ± 0.43	9	0.245	5,35
3	0.82 ± 0.19	8	0.165	5,35
4	0.56 ± 0.23	13	0.145	5,35
8	0.99 ± 0.57	10	0.207	5,35
11	0.96 ± 0.43	15	0.180	5,35

Average ± standard deviation

E_1 $(0.84 \pm 0.17)\times10^{-7}$ J/break

Initial elongation per break 0.188 ± 0.039 %/break

Table 15.

Tests on Unbeaten Southern Pulp Handsheets Pressed at 350 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break	MINBK, MAXBK
4	1.29 ± 0.47 [1]	13	0.873	5,15
6	1.30 ± 0.58 [1]	13	0.836	5,15
11	1.36 ± 0.70	9	1.811	1,10
14	2.01 ± 0.56	11	1.171	1,15
15	1.20 ± 0.54	9	2.019	1,10

Average ± standard deviation

E_1 (1.43 ± 0.33)x10^{-7} J/break

Initial elongation per break 1.342 ± 0.544 %/break

Table 16.

Tests on Unbeaten Southern Pulp Handsheets Pressed at 660 kPa

Specimen	E_1 ± std. dev. 10^{-7} J/break	Number of breaks	Init. elong. per break %/break	MINBK, MAXBK
3	1.89 ± 0.83	15	1.500	1,15
6	1.37 ± 0.43	8	2.157	1,10
10	0.77 ± 0.41	10	1.172	1,10
11	1.20 ± 0.87	13	1.003	1,15
19	1.83 ± 1.14	13	2.219	1,15

Average ± standard deviation

E_1 (1.41 ± 0.47)x10^{-7} J/break

Initial elongation per break 1.610 ± 0.557 %/break

Supplementary Information - Tables 13, 14, 15, 16.

For computation of E_1:

Maximum force drop D 0.196 mN (0.02 g)

Minimum force H	(Tables 13, 14)	0.981 mN (0.1 g)
	(Tables 15, 16)	0.0 mN except for
	1.	0.392 mN (0.04 g)

Average E_1 is the unweighted average of E_1 values for each specimen.

Initial elongation per break:

Values of initial elongation per break were obtained by a least squares fit of data points ranging from a minimum break (MINBK) through a maximum break (MAXBK).

Table 17.

Summary of Results for Unbeaten Northern Pulp Handsheets

Identification	Forming pressure kPa	E or E_1 ± std. dev. 10^{-7} J/break	Init. elong. per break %/break
(graph) 1/	44	0.76 ± 0.10	0.164 ± 0.039
Table 13 (comp.)	350	1.04 ± 0.10	0.210 ± 0.072
Table 14 (comp.)	660	0.84 ± 0.17	0.188 ± 0.039

Table 18.

Summary of Results for Unbeaten Southern Pulp Handsheets

Identification	Forming pressure kPa	E or E_1 ± std. dev. 10^{-7} J/break	Init. elong. per break %/break
(graph) 1/	44	0.88 ± 0.31	0.520 ± 0.240
Table 15 (comp.)	350	1.43 ± 0.33	1.342 ± 0.544
Table 16 (comp.)	660	1.41 ± 0.47	1.610 ± 0.557

1. From previous report [2].

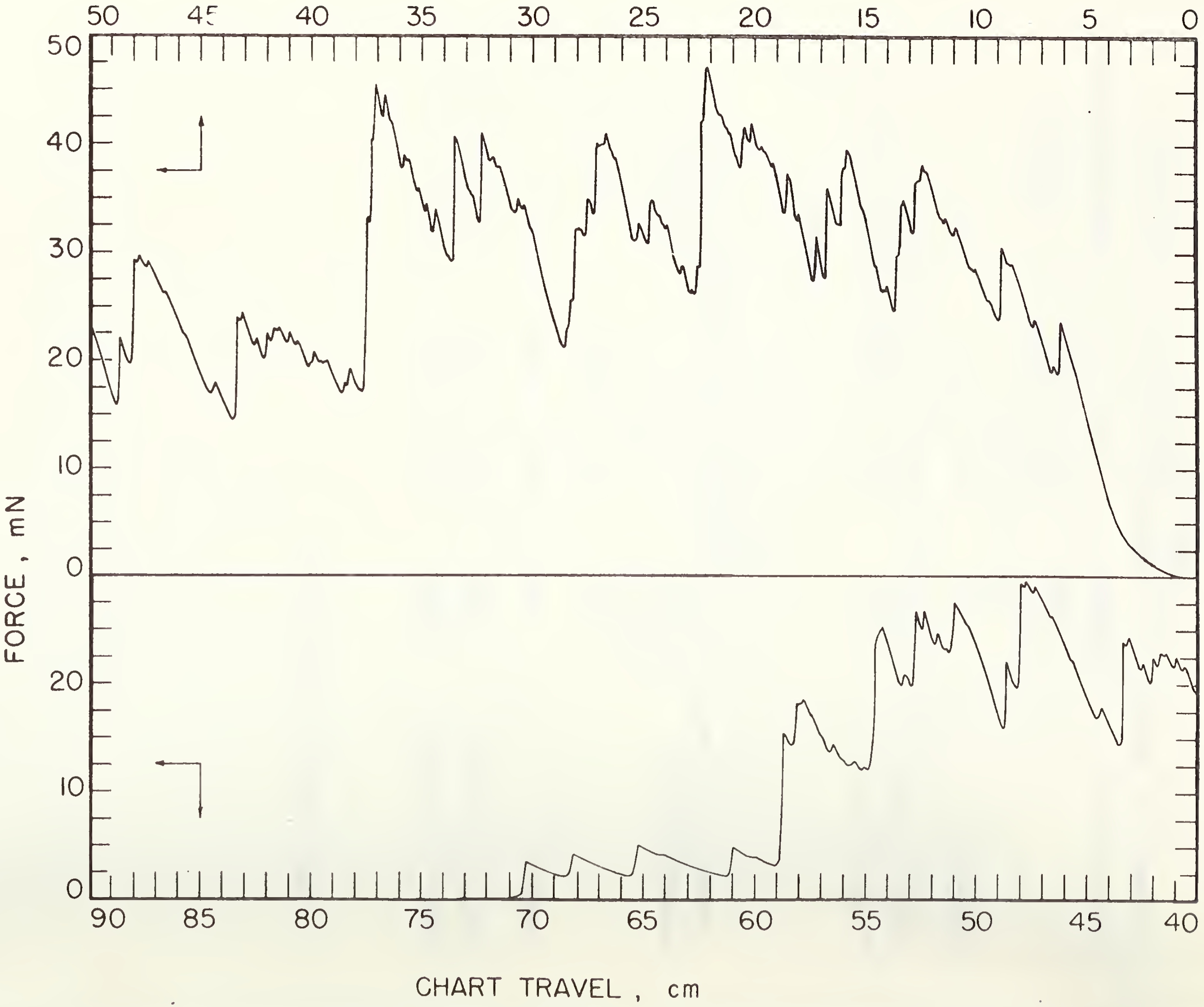

Figure 1. Tracing of force-elongation curve for specimen 12 of the beaten

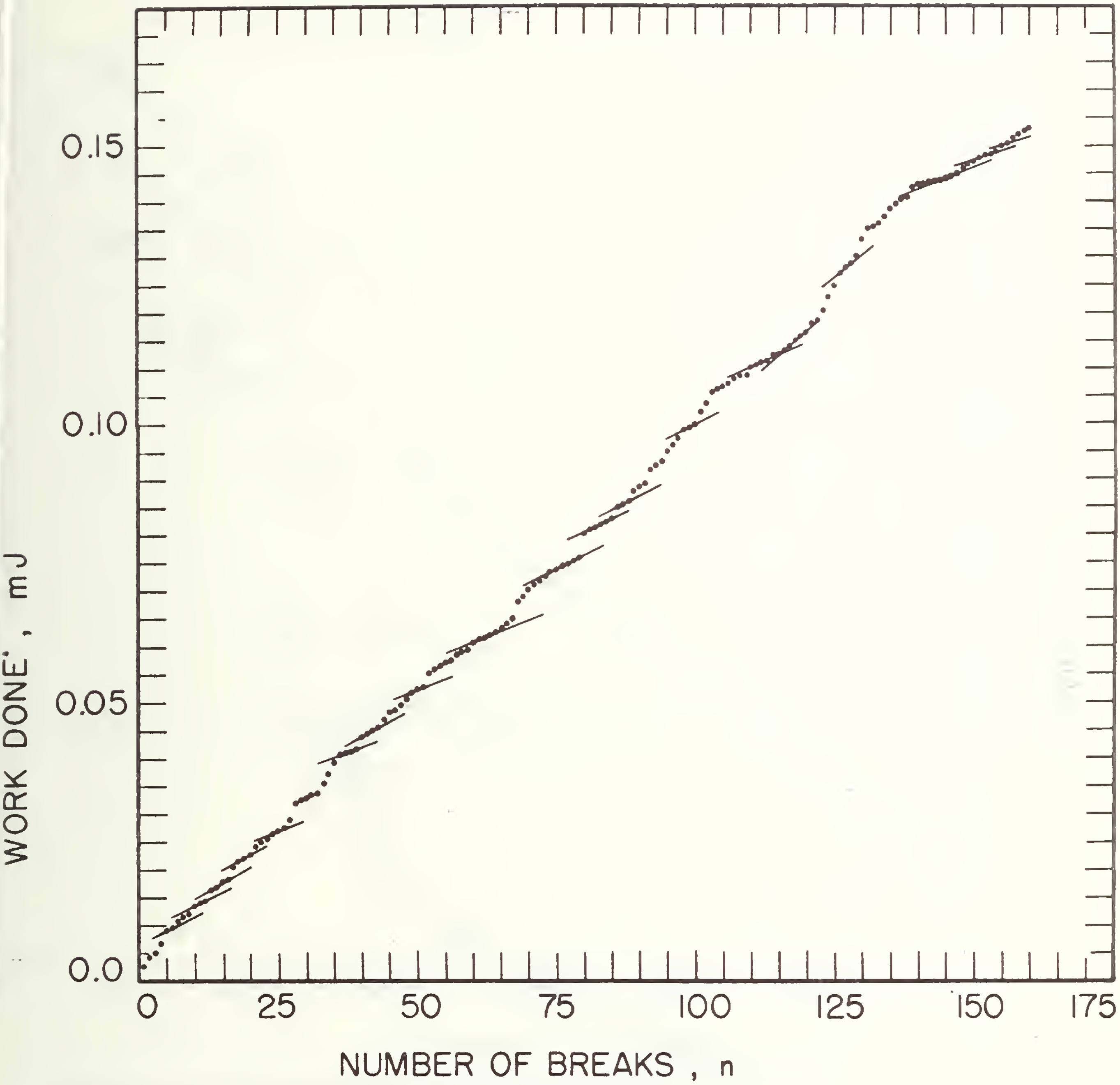

Figure 2. Plot of work of extension versus number of bond breaks for specimen 12 of the beaten Southern pulp handsheet pressed at 44 kPa.

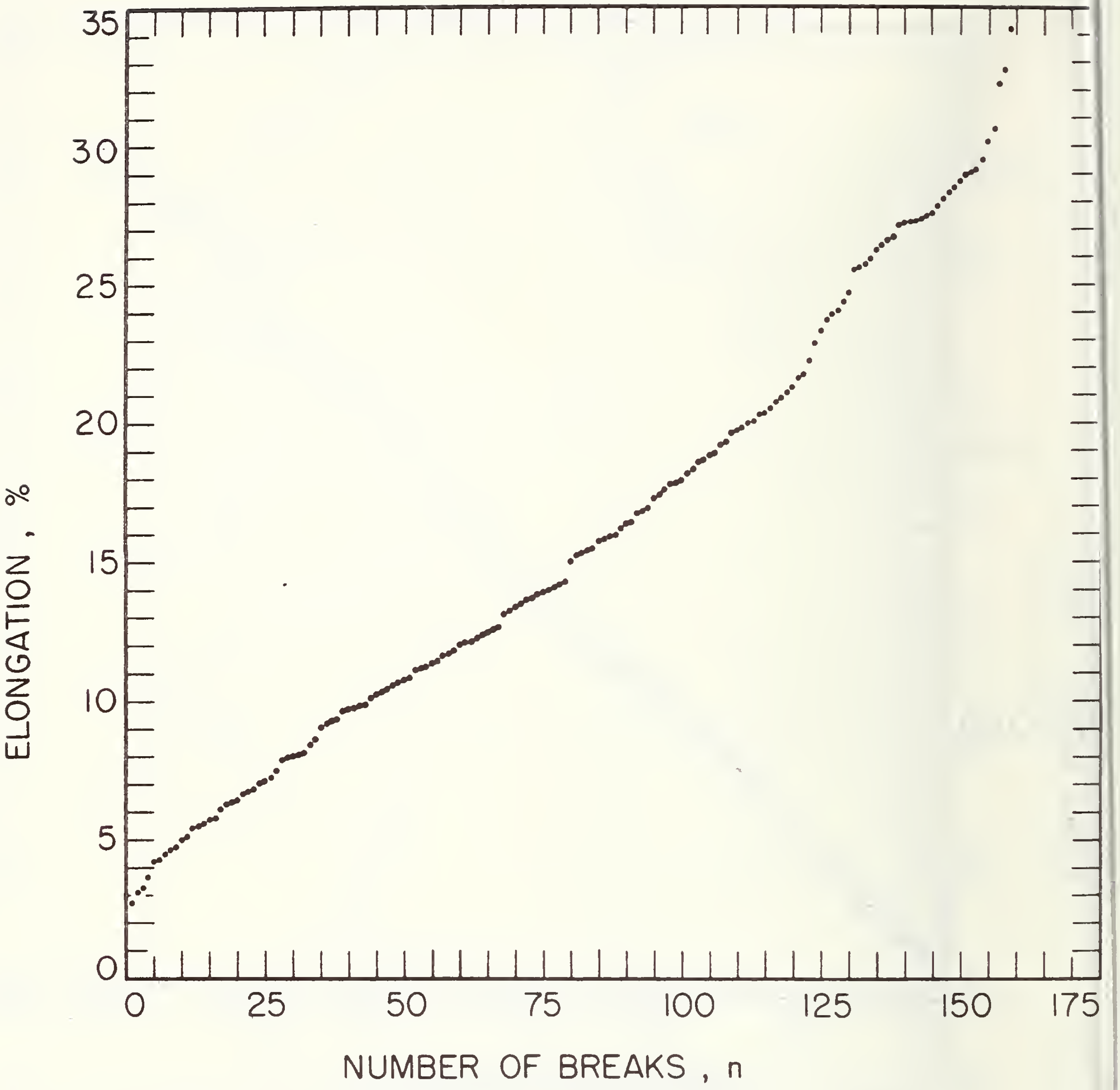

Figure 3. Plot of elongation versus number of bond breaks for specimen 12 of the beaten Southern pulp handsheet pressed at 44 kPa.

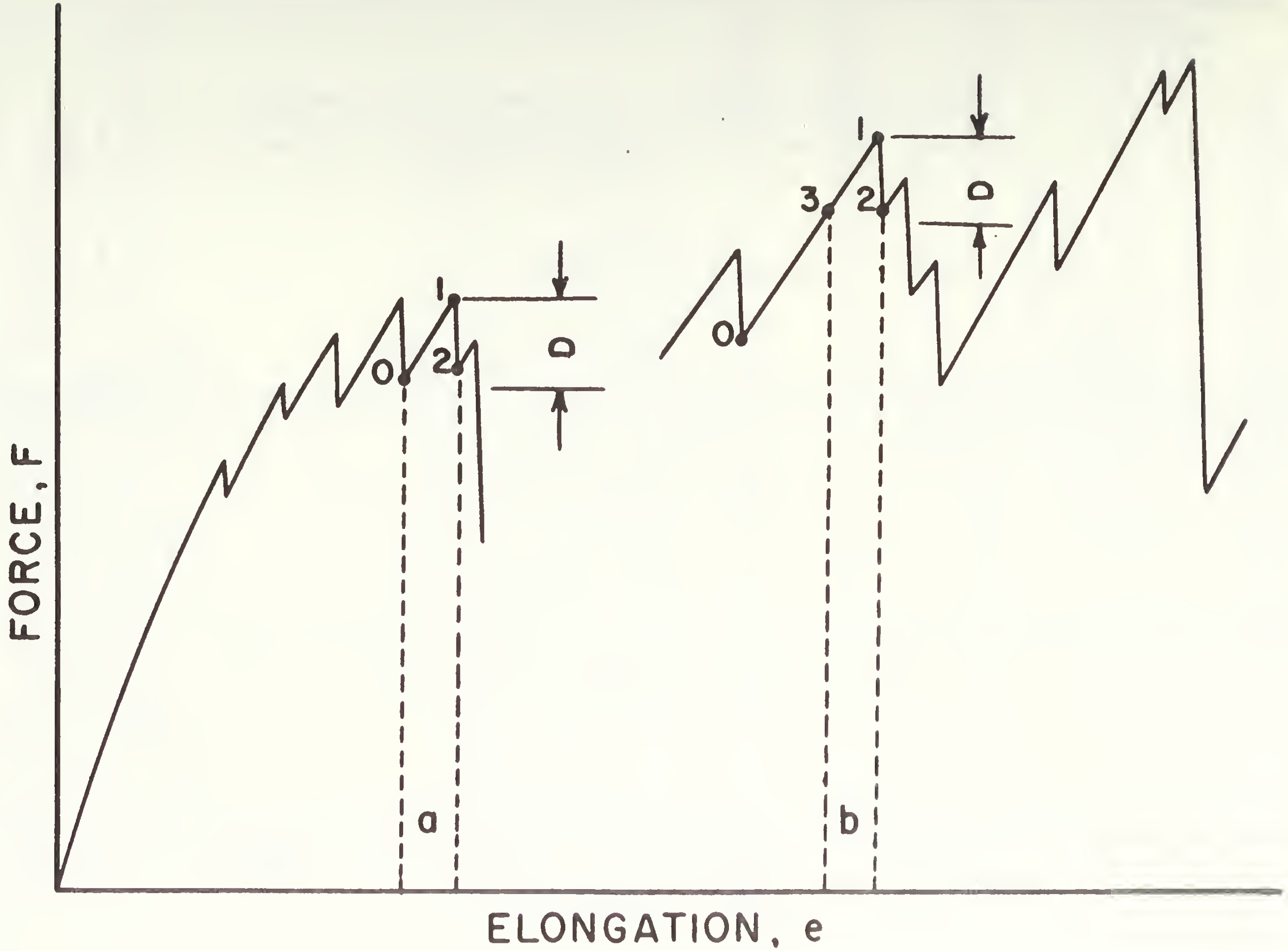

Figure 4. Situations encountered in calculation of energy dissipation.

a. Force rise $F_1 - F_0$ is less than force drop parameter D.

b. Force rise $F_1 - F_0$ exceeds D.

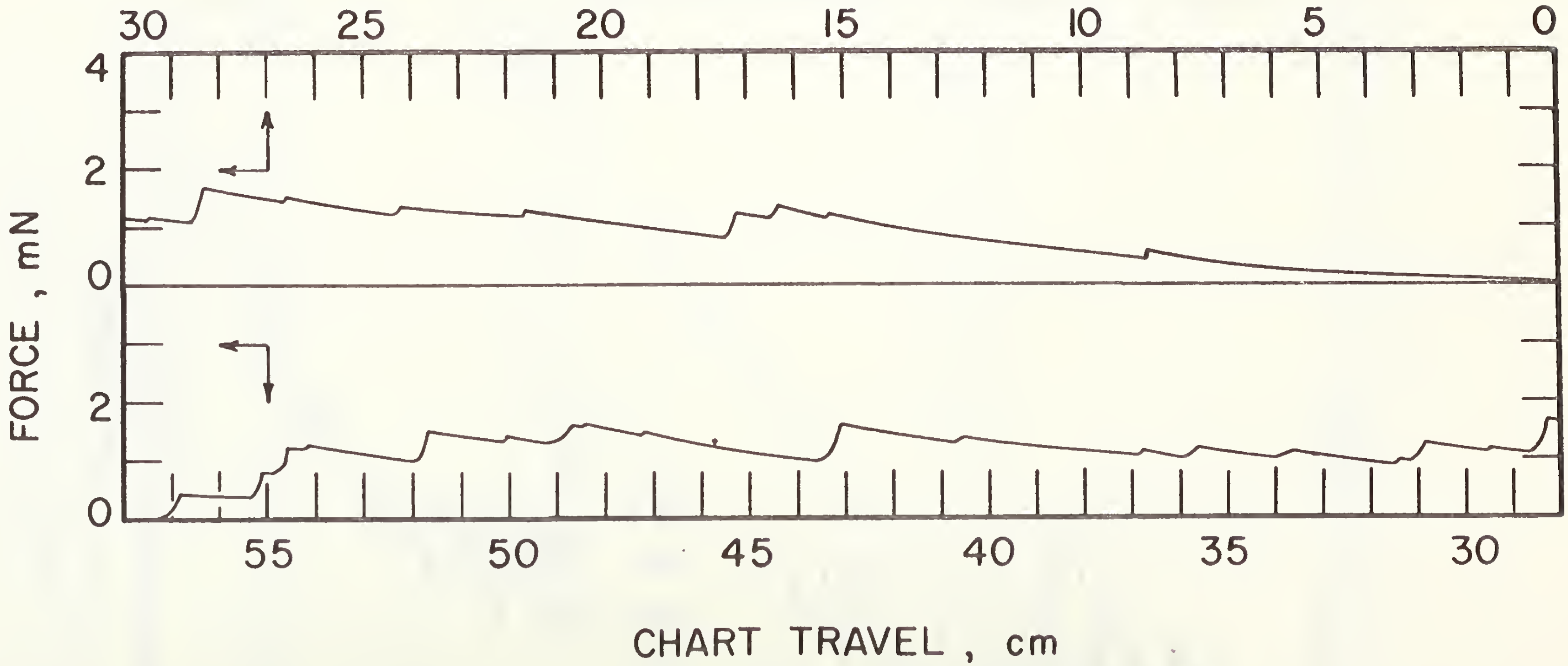

Figure 5. Tracing of force-elongation curve for specimen 11 of the unbeaten Southern pulp handsheet pressed at 660 kPa.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Handsheets in the form of low-density open webs of grammage 2.5 g/m^2 were prepared from Northern and Southern softwood kraft pulps. These handsheets, from pulps unbeaten and beaten for 5,000 revolutions in a laboratory beater, were pressed at 44, 350 and 660 kPa (6.4, 51.2 and 96 lb/in^2) during preparation. The relative density of bonding between fibers and the relative strength of the bonds were estimated from tensile strength data. It was found that the quality of bonding between fibers in the webs was not affected by preparation pressures between 44 kPa and 660 kPa, but webs prepared at the higher pressure tended to stick to the backing plate, thus incurring some damage upon removal.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Paper, interfiber bonding; paper, low-density handsheets; paper, pulp characterization; paper, tensile testing; paper, recycling; mixed waste paper.

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