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EFFECT OF FLEXING ON THE MECHANICAL PROPERTIES OF PAPER

E. L. GRAMINSKI, Paper Evaluation Section, Institute for Materials Research, National Bureau of Standards, Washington, D.C., U.S.A.

Synopsis Probable causes for the deterioration of the physical properties of paper as a result of repeated handling have been determined. A flexing test has been devised that evaluates the relative durability of paper.

Investigations with the scanning electron microscope indicate that the fibrillar component of paper deteriorates during flexing and is probably responsible for the decline in stiffness as well as the modulus of paper. Because of the ever-increasing use of automatic document handling equipment, stiffness retention with handling is essential, since limp documents are difficult, if not impossible, to process automatically. Unfortunately, stiffness declines rapidly as paper is flexed or handled.

The rates of deterioration for all other physical properties of paper during flexing are independent of each other and vary from one paper to another. The rate at which certain properties deteriorate is independent of the quality of the paper.

No correlation has been found between any paper property and durability.

Introduction

THE durability of paper is defined as 'the degree to which a paper retains its original qualities under continual usage'.[1] Generally, paper does not remain in a plane when handled, but is bent and flexed to some degree. This bending and flexing is considered to be partly responsible for the deterioration of physical properties during use. In as much as paper frequently is subjected to bending stresses, a laboratory test that would predict durability in terms of bending stresses should be useful.

A paper flexing machine (Fig. 1) has been designed and constructed to accelerate the deterioration of the properties of paper through flexing in a uniform and reproducible manner. A sheet of paper is flexed first in one direction, then in the other—by a pair of rollers that is drawn back and forth by a reciprocating mechanism. The percentage retention of physical properties is plotted against the number of flexes; the slope of the plot, as well as the

Under the chairmanship of Dr H. G. Higgins extent of the decline of physical properties, may be considered a measure of the durability of paper.

An attempt was made to flex papers at approximately the same level of internal stress with respect to machine-direction (MD) and cross-direction

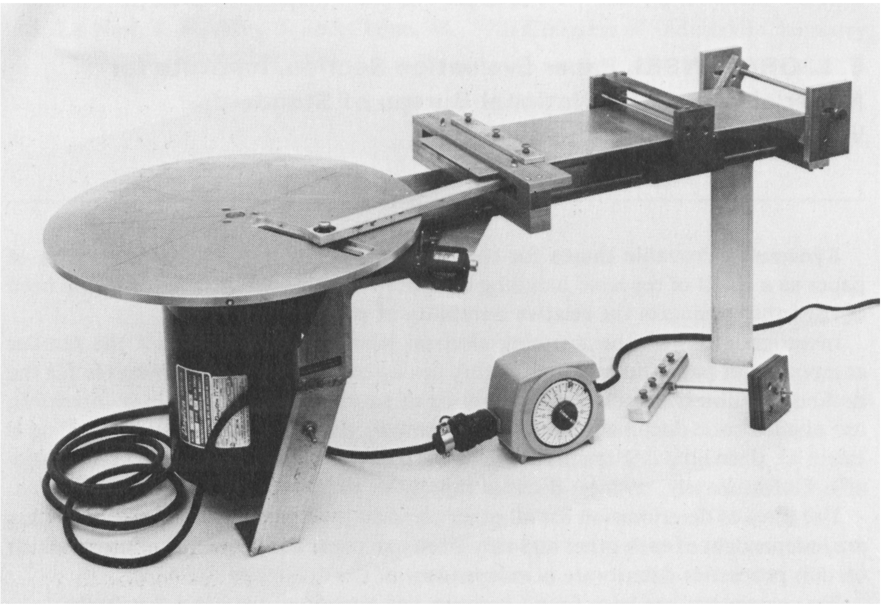

Fig. 1—Paper flexing apparatus

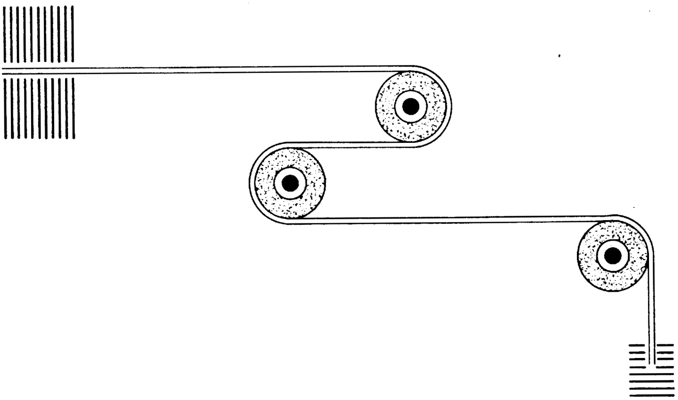

Fig. 2—Schematic diagram for paper flexing

(CD). The relationship between the bending moment and the deformation is given by—

$$\frac{M}{I} = \frac{E}{R}$$

where M = bending moment
I = second moment of area of the section about the neutral plane
E = Young's modulus
R = radius of curvature

Assuming that I is identical in both MD and CD, M will be greater in the MD than in the CD for any value of R, as E is usually 2–2·5 times greater in the MD than in the CD. Therefore, all flexing was done over 3·18 mm diameter rollers in the CD and 7·94 mm diameter rollers in the MD. The ratio of these diameters is 2·5.

EXPERIMENTAL DETAILS

Flexing

THE flexing apparatus is shown pictorially in Fig. 1 and schematically in Fig. 2. A pair of flexing rollers is mounted on a head that moves back and forth in a guide mechanism similar to the travel of the carriage on the ways of a metal turning lathe. The flexing head is attached to a connecting rod that, in turn, is attached to a crank (a 15 in diameter wheel). Rotation of the wheel at 30 rev/min by a motor with a gear-reducing head supplies the reciprocating motion for the flexing head. The wheel is slotted to allow adjustment of the length of the stroke. One revolution of the wheel results in two double flexes of the paper. A counter is positioned near the edge of the wheel.

The principle of the flexing action is illustrated in Fig. 2. The paper (15·2 cm × 30·5 cm) is clamped at one end, threaded over the rollers as shown, over the stationary roller and constrained with a 700 g weight clamped to the other end of the sheet. Paper leaders taped to each end of the sample allow the maximum area of experimental paper to be flexed.

After the sample had received the desired number of flexes, the double-flexed area was marked, removed and trimmed so as to include only the double flexed area. The trimmed sheets were approximately 15·2 cm × 20·3 cm.

Testing

AIR permeability was measured with the Carson-Worthington air permeameter[2] before cutting the flexed sheets into specimens according to the scheme shown in Fig. 3.

Cantilever stiffness was measured with the Carson-Worthington stiffness tester.[3] These same specimens were then used for the determination of internal tearing strength according to TAPPI T414 ts-65. A single specimen was

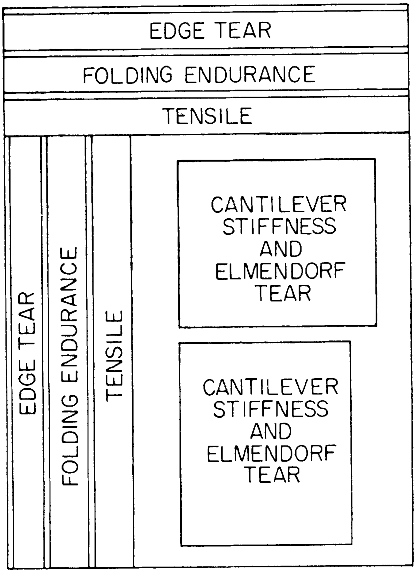

Fig. 3—Specimen layout for flexed samples

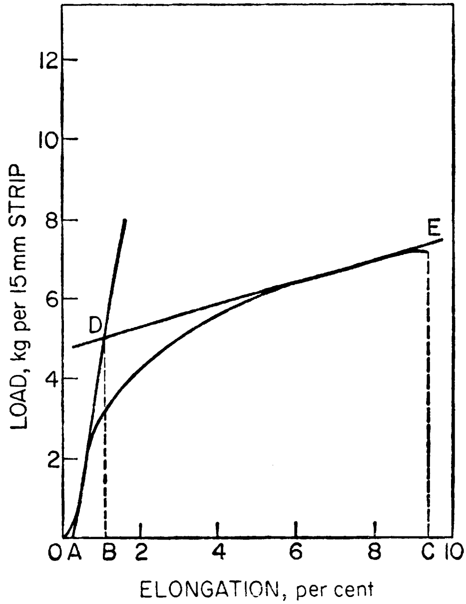

Fig. 4—Typical load/elongation curve for paper

used for equal determination on an Elmendorf tear tester with a capacity of 200 g.

Folding endurance was carried out according to TAPPI T 511 su-69, using an MIT folding endurance tester.

Load/elongation was performed on a constant rate of loading apparatus according to TAPPI T404 ts-66, using a specimen 1·5 cm wide and a span length of 10 cm.

Analysis of load/elongation curves

A LINE (AD) was drawn tangentially to the initial straightline portion of the load/elongation curve (Fig. 4) and another line (DE) was drawn tangentially to the straightline portion of the latter protion of the curve. The slopes of lines AD and DE were used to determine the initial stiffness and the plastic stiffness, respectively. These are the slopes of the load/strain curve at the beginning and end of each load/elongation curve. The two moduli can be determined for each specimen by dividing the stiffness values by the cross-sectional area. Since paper does not exhibit a well-defined yield region, the intersection of lines AD and DE was defined as the load at yield and OB was defined as the elongation at yield. The distance OC is the elongation at break.

Scanning electron microscopy

SCANNING electron microscopy (SEM) samples were mounted with conductive silver paint on 12 mm stubs and were coated with gold by R-F sputtering. Flexed paper specimens were mounted over 3·18 mm diameter mandrels and secured at the ends with a small cotter pin. These specially prepared specimens were mounted on 12 mm stubs having a 3 mm slot to accommodate the cotter pin. The prepared specimens were examined with an SEM at a gun potential of 10 kV.

RESULTS

THREE papers were used in this investigation, a high grade rag, an all cotton ledger and newsprint. From experience, it was known that the high grade rag was the most durable of the three papers, newsprint was the least durable and ledger paper was intermediate in durability.

In general, deterioration of the physical properties of all three papers occurred primarily in the direction of flexing with substantially less deterioration in the opposite direction (Tables 1 and 2). The physical properties degraded at varying rates and to different extents (Fig. 5–7). Elmendorf tear usually declined least, whereas the cantilever stiffness decreased rapidly and extensively. The order for the retention of physical properties was not the same for all papers nor was the order the same in both the cross and machine directions for a single paper.

The extent to which certain properties degraded was independent of the quality of the paper. For example, retention of energy to break in both cross and machine directions for high grade rag was less than that of newsprint, a paper considered many orders of magnitude lower in quality.

The decline of folding endurance in newsprint was unusual. A very large decrease in folding endurance occurred in the early stages of flexing, but this was not evident in the other papers. The reasons for this extensive decline in folding endurance of newsprint is not known; however, it apparently is not due to a decrease in interfibre bonding, since breaking strength did not decline appreciably during this same interval of flexing.

Air permeability increased rapidly during the early stages of flexing. Apparently, the structural changes occurring during flexing, leading to an increase in porosity, are responsible for the large decreases in modulus and cantilever stiffness.

There is a large decrease in the initial stiffness of paper at the onset of flexing for all papers studied (Fig. 8–10). The decrease in initial stiffness is greatest when paper is flexed in the CD. It will be shown later that the decrease in initial stiffness is related to the radius of curvature of the rollers used in flexing. The decrease in initial stiffness occurs almost entirely during the first thousand flexes with only a slight decrease occurring as flexing proceeds.

TABLE 1—LOAD/ELONGATION PROPERTIES OF FLEXED PAPER

No. of flexes 1 000	*No. of specimens*	*Extensional stiffness, kN/m*				*Plastic stiffness, kN/m*				*Breaking strength, kN/m*			
		MD	*s*(*)	*CD*	*s*	*MD*	*s*	*CD*	*s*	*MD*	*s*	*CD*	*s*
High grade rag flexed in CD over 3·18 mm rollers													
0	15	588	42	324	18	91	6	26	2	7·3	0·3	4·6	0·2
5	15	523	30	220	12	93	7	26	2	6·9	0·4	5·6	0·2
10	15	471	27	213	11	89	8	25	2	7·3	0·5	4·5	0·2
20	15	552	28	220	16	86	5	25	2	6·9	0·5	4·2	0·3
80	14	522	23	220	12	86	7	29	4	7·0	0·4	3·1	0·2
High grade rag flexed in MD over 7·94 mm rollers													
0	15	588	23	324	18	91	6	26	2	7·3	0·3	4·6	0·2
10	12	530	27	299	8	88	9	25	2	7·0	0·3	4·6	0·3
20	12	488	41	267	17	98	12	24	2	6·4	0·3	4·6	0·1
40	13	502	25	302	13	111	31	23	2	5·0	0·6	4·4	0·1
Cotton ledger flexed in CD over 3·18 mm rollers													
0	14	606	40	295	15	118	9	27	4	6·2	0·2	3·5	0·1
20	12	525	34	163	13	153	22	31	5	5·2	0·6	3·3	0·2
40	12	512	18	141	9	141	23	30	4	5·6	0·3	3·2	0·1
80	12	503	20	153	7	173	29	32	5	5·1	0·5	3·1	0·1
Cotton ledger flexed in MD over 7·94 mm rollers													
0	15	705	16	335	20	127	8	25	3	6·6	0·3	3·6	0·2
5	15	543	15	273	16	115	9	22	3	6·2	0·2	3·4	0·2
10	14	549	14	301	22	116	16	14	1	5·8	0·3	3·5	0·4
20	15	533	13	292	12	135	15	24	2	5·4	0·2	3·5	0·2
40	15	503	10	288	25	179	33	23	3	4·5	0·3	3·5	0·2
Newsprint flexed in CD over 3·18 mm rollers													
0	16	327	11	97	5	184	31	23	8	2·3	0·2	0·9	0·1
10	16	278	8	54	3	161	15	25	5	2·0	0·1	0·8	0·1
20	16	282	16	53	3	158	24	26	4	2·0	0·2	0·7	0·1
40	12	275	15	48	3	151	25	24	3	1·9	0·3	0·7	0·1
80	15	268	8	44	3	167	18	26	3	1·8	0·2	0·5	0·1
Newsprint flexed in MD over 7·94 mm rollers													
0	14	326	14	97	4	184	24	25	4	2·1	0·2	0·9	0·1
2	14	263	15	90	7	180	16	25	5	1·9	0·3	0·9	0·1
5	12	227	9	84	5	171	12	22	3	1·7	0·1	0·8	0·1
10	15	232	9	88	3	158	22	24	4	1·6	0·2	0·8	0·1
20	15	210	7	84	7	162	9	26	6	1·4	0·1	0·8	0·1
40	14	193	12	82	7	137	12	24	5	1·2	0·1	0·8	0·1

(*) $s = \sqrt{\dfrac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}}$

TABLE 1—(*contd.*)

Elongation to break, per cent				Energy to break, J/m^2				Load at yield, kN/m				Elongation at yield, per cent			
MD	*s*	*CD*	*s*	*MD*	*s*	*CD*	*s*	*MD*	*s*	*CD*	*s*	*MD*	*s*	*CD*	*s*
4·3	0·4	9·3	0·9	209	26	288	33	4·2	0·1	2·7	0·1	0·5	0·05	0·6	0·04
4·1	0·3	9·3	1·0	190	26	294	39	3·9	0·2	2·6	0·1	0·5	0·02	0·8	0·07
4·4	0·3	8·6	0·9	216	20	275	39	4·3	0·3	2·7	0·2	0·6	0·04	0·8	0·05
4·2	0·3	7·7	1·0	196	26	229	46	4·1	0·2	2·7	0·1	0·5	0·03	0·8	0·06
4·3	0·2	4·8	0·9	203	20	105	26	4·1	0·3	2·0	0·2	0·5	0·03	0·6	0·04
4·3	0·4	9·3	0·9	209	26	288	33	4·2	0·1	2·7	0·1	0·5	0·05	0·6	0·04
4·0	0·3	8·3	0·8	190	20	275	33	4·2	0·2	2·7	0·2	0·5	0·02	0·6	0·05
3·3	0·5	9·0	0·7	144	26	301	26	4·1	0·1	2·8	0·1	0·5	0·05	0·7	0·16
2·2	0·6	8·5	0·8	72	26	275	33	3·6	0·4	2·7	0·1	0·5	0·05	0·6	0·03
2·5	0·2	5·3	0·7	111	13	144	20	4·2	0·1	2·4	0·1	0·5	0·01	0·6	0·03
2·0	0·3	5·2	0·7	72	20	118	26	3·4	0·5	2·3	0·2	0·5	0·05	0·9	0·09
2·4	0·2	6·0	0·5	92	13	124	13	3·4	0·3	2·0	0·1	0·5	0·04	1·0	0·11
2·1	0·3	5·5	0·6	72	20	111	20	2·9	0·3	2·0	0·1	0·4	0·03	0·8	0·07
2·5	0·2	5·5	0·8	111	13	150	26	4·4	0·1	2·5	0·2	0·5	0·01	0·5	0·02
2·5	0·2	6·4	0·7	98	13	163	20	4·4	0·1	2·4	0·1	0·6	0·02	0·7	0·03
2·1	0·9	6·1	0·6	78	13	163	13	4·1	0·2	2·4	0·1	0·5	0·03	0·6	0·03
2·0	0·2	5·6	0·9	65	7	145	26	4·0	0·2	2·4	0·1	0·5	0·03	0·6	0·02
1·6	0·2	6·3	0·7	46	13	163	20	3·1	0·3	2·4	0·1	0·5	0·05	0·6	0·04
0·8	0·1	1·8	0·3	10	6	27	3	1·6	0·2	0·7	0·1	0·3	0·05	0·5	0·07
0·9	0·1	2·0	0·4	9	1	22	1	1·5	0·1	0·5	0·1	0·4	0·04	0·6	0·10
0·9	0·1	1·9	0·2	9	2	8	1	1·5	0·1	0·5	0·1	0·4	0·05	0·6	0·08
0·9	0·1	1·9	0·2	9	2	7	1	1·4	0·1	0·4	0·1	0·4	0·03	0·6	0·07
0·8	0·1	1·6	0·2	9	2	5	1	1·4	0·2	0·3	0·1	0·3	0·04	0·5	0·08
0·8	0·1	1·9	0·1	10	2	12	2	1·6	0·1	0·7	0·1	0·3	0·03	0·5	0·04
0·8	0·1	1·9	0·2	9	3	11	2	1·4	0·3	0·7	0·1	0·3	0·05	0·5	0·04
0·8	0·1	1·9	0·2	8	1	11	1	1·3	0·1	0·6	0·1	0·4	0·05	0·5	0·04
0·8	0·1	1·9	0·2	7	1	11	2	1·2	0·2	0·7	0·1	0·3	0·05	0·5	0·04
0·7	0·1	1·8	0·3	5	1	9	3	1·0	0·1	0·6	0·1	0·3	0·05	0·5	0·06
0·7	0·1	1·8	0·2	5	1	10	2	0·9	0·1	0·6	0·1	0·3	0·04	0·5	0·06

TABLE 2—PHYSICAL PROPERTIES OF FLEXED PAPER

No. of flexes 1 000	No. of specimens	Elmendorf tear, g MD	s(2)	CD	s	Folding endurance, double folds, MIT, 1 000 g MD	s	CD	s	Cantilever stiffness, g/cm MD	s	CD	s	Air permeability, csm(1)	s
High grade rag flexed in CD over 3·18 mm rollers															
0	15	106	20	98	14	5 810	1 030	6 150	1 680	4·4	0·5	2·1	0·12	0·7	0·14
5	15	91	17	91	11	5 590	1 300	5 650	1 340	4·0	0·4	1·3	0·08	3·8	0·54
10	15	100	14	98	18	6 780	1 830	5 640	1 100	3·9	0·4	1·2	0·07	5·4	0·74
20	15	88	15	97	14	6 470	1 050	5 210	1 920	3·9	0·3	1·0	0·06	7·4	0·81
80	14	84	7	89	13	5 450	850	3 060	1 440	3·4	0·3	0·8	0·08	9·7	1·27
High grade rag flexed in MD over 7·94 mm rollers															
0	15	106	20	98	14	5 810	1 030	6 150	1 680	4·4	0·5	2·1	0·1	0·7	0·14
10	12	104	23	97	16	6 090	1 510	5 550	1 130	3·3	0·4	1·8	0·2	1·7	0·74
20	12	96	17	92	11	5 390	1 730	6 120	1 920	3·4	0·4	1·9	0·1	2·3	0·54
40	13	93	15	89	15	4 030	1 140	5 440	2 330	3·0	0·3	1·8	0·1	4·0	0·59
Cotton ledger flexed in CD over 3·18 mm rollers															
0	14	131	15	122	36	1 020	170	540	150	4·5	0·3	2·4	0·2	93	7
20	12	123	7	114	12	1 040	470	520	150	3·3	0·2	0·8	0·05	128	15
40	12	109	13	116	12	920	190	380	100	3·3	0·2	0·8	0·05	131	19
80	12	106	10	112	9	940	170	260	60	3·1	0·1	0·7	0·05	132	10
Cotton ledger flexed in MD over 7·94 mm rollers															
0	15	135	15	138	16	1 300	350	610	180	5·0	0·3	2·5	0·2	98	8
5	15	127	12	134	18	1 070	290	450	170	3·3	0·1	2·1	0·2	116	27
10	14	127	13	130	22	840	270	420	110	3·0	0·2	2·0	0·3	110·	14
20	15	116	9	119	17	780	350	500	110	2·8	0·2	2·0	0·2	112	8
40	15	123	9	115	11	590	310	460	170	2·7	0·2	2·0	0·2	125	9
Newsprint flexed in CD over 3·18 mm rollers															
0	16	17	1	26	2	260	90	40	20	1·7	0·05	0·6	0·04	766	131
10	16	15	2	24	1	180	110	15	5	1·3	0·05	0·2	0·01	838	140
20	16	13	1	18	2	210	100	13	6	1·3	0·06	0·2	0·01	756	115
40	12	13	2	20	1	160	80	10	4	1·3	0·05	0·2	0·01	789	158
80	15	13	1	19	1	130	80	6	4	1·3	0·03	0·2	0·01	878	125
Newsprint flexed in MD over 7·94 mm rollers															
0	14	19	2	25	2	200	95	27	18	1·7	0·07	0·6	0·04	794	108
2	14	17	1	22	2	100	65	27	13	1·0	0·04	0·5	0·03	765	146
5	12	17	2	22	2	50	30	22	10	0·9	0·04	0·5	0·03	881	136
10	15	16	1	20	0·2	40	30	25	13	0·8	0·02	0·5	0·02	803	114
20	15	16	1	19	1	50	20	20	7	0·7	0·03	0·4	0·03	833	174
40	14	13	2	16	2	30	10	20	10	0·7	0·03	0·5	0·03	801	153

(1) $s = \sqrt{\frac{n\Sigma X^2 - (\Sigma X)^2}{n(n-1)}}$

(2) csm = one cubic centimeter of air per second through an area of one square metre when impelled by a pressure difference of 98·07 newton/metre²

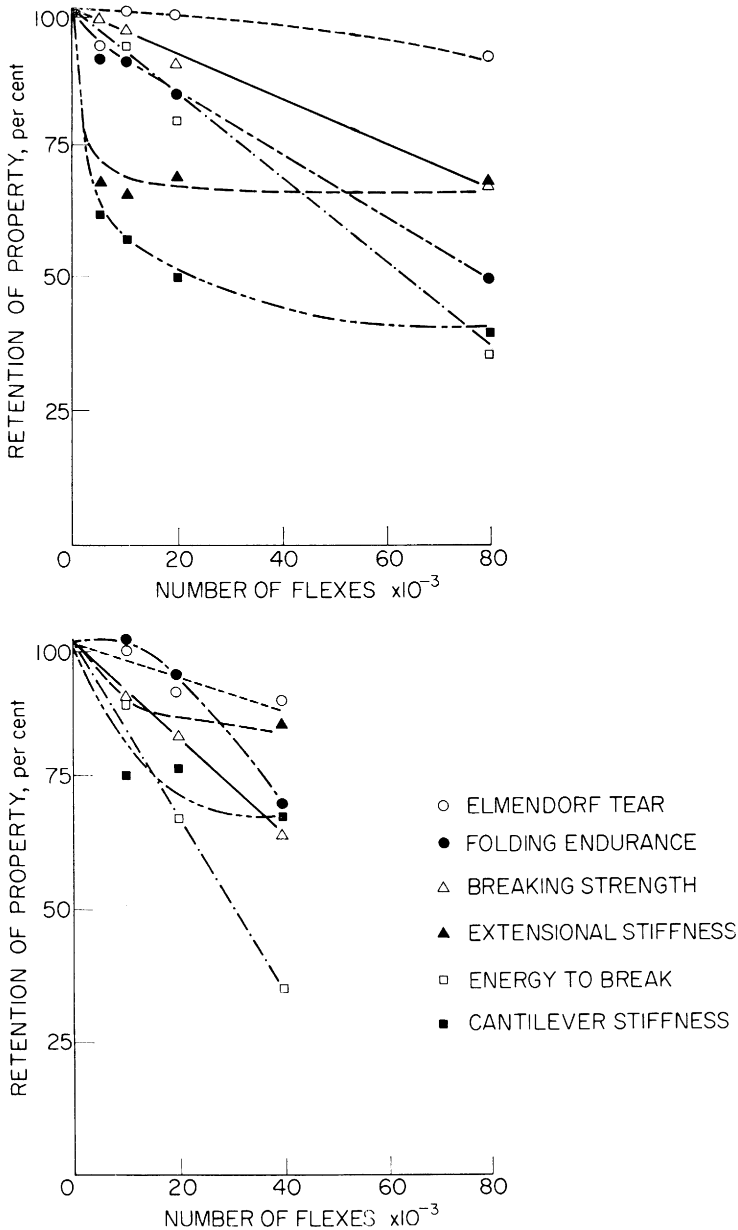

Fig. 5—Degradation of physical properties of high grade rag paper during flexing

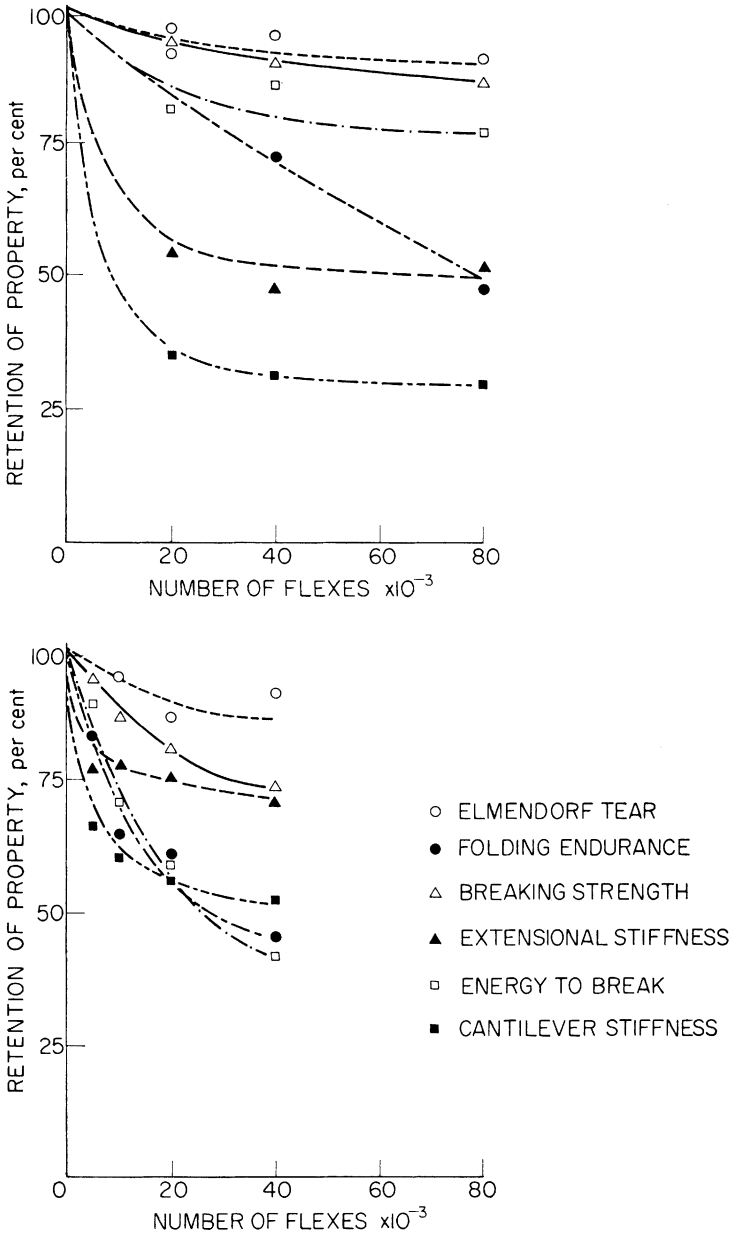

Fig. 6—Degradation of physical properties of cotton ledger paper during flexing

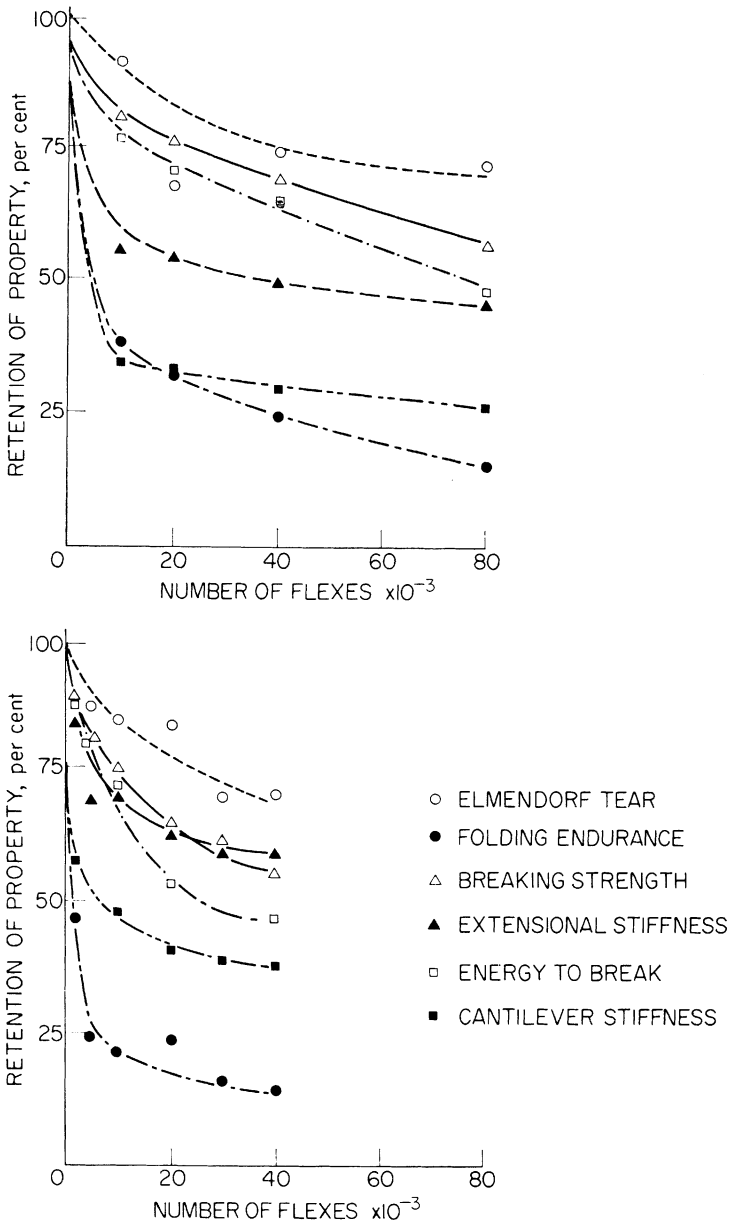

Fig. 7—Degradation of physical properties of newsprint during flexing

The rate of decline in breaking strength is moderate at first and usually decreases progressively with flexing. The extent of decline is not a function of the paper quality. When flexed in the CD, the ledger paper retained its strength most, whereas the high grade rag paper retained its strength only slightly better than newsprint. When flexed in the MD, both ledger and high grade rag papers were superior to newsprint.

Retention of elongation to break of newsprint was surprisingly good when flexed in either direction. Essentially, no decrease in elongation to break occurred in the ledger paper when flexed in the CD, but an appreciable decline did occur during flexing in the MD. The high grade rag paper exhibited a substantial decline in elongation when flexed in both CD and MD.

An increase in plastic stiffness during flexing usually parallels an appreciable decrease in elongation to break. As the elongation to break decreases, the load/elongation curve becomes shorter and the tangent line at the latter portion of the curve is drawn in a region of greater slope, resulting in an increase in plastic stiffness.

When the decrease in initial stiffness is extensive and all other tensile properties remain essentially unchanged, the two slopes intersect at a point further away from the origin, resulting in an increase in elongation at yield. When elongation to break decreases as flexing proceeds, the intersection of the two tangent lines occurs at some point closer to the origin, resulting in a subsequent decrease in elongation at yield. Load at yield decreases in all instances with flexing, primarily in the direction of flexing.

The original intent in this project was to flex paper at equal levels of internal stress, but individuals handling documents do not give special consideration to the anisotropy of paper. As a result, both directions may be subjected to the same degree of bending strain. Therefore, it was of interest to determine the effect of the same bending strain during flexing in the MD of paper as in the CD on the retention of physical properties.

The high grade rag paper was used in this study. In general, deterioration was more extensive when the paper was flexed in the MD over 3·18 mm diameter rollers than over 7·94 diameter rollers. The deterioration of properties in the MD, when flexed in the MD over 3·18 mm rollers, was greater than the deterioration of properties in the CD after flexing in the CD on the same size rollers. A comparison of the extent of decline of some properties, as a function of strain level, is shown in Fig. 11 & 12. The effect of roller size on the load/elongation curve is shown in Fig. 11.

Apparently, more fibre-to-fibre bonds are broken and/or fibres are broken when paper is flexed in the MD over 3·18 mm rollers than when flexed over 7·94 mm rollers, since the decrease in breaking strength is much greater when paper is flexed in the MD over the smaller radius rollers.

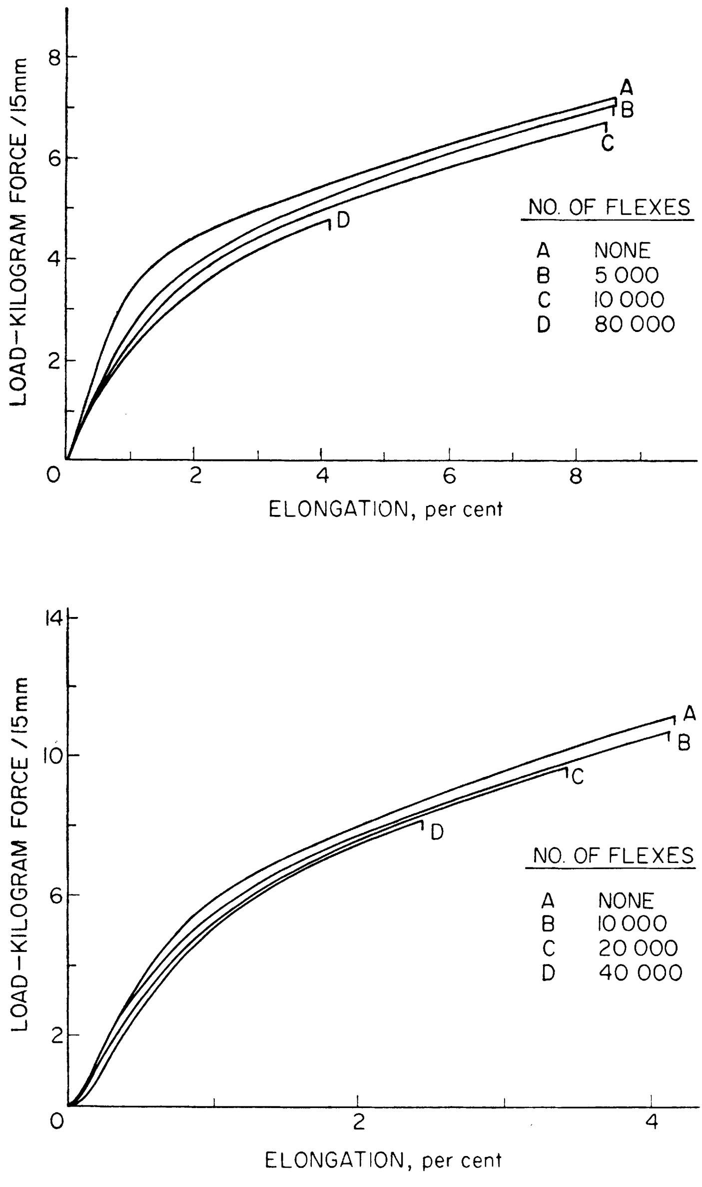

Fig. 8—Load/elongation curves for flexed high grade rag paper

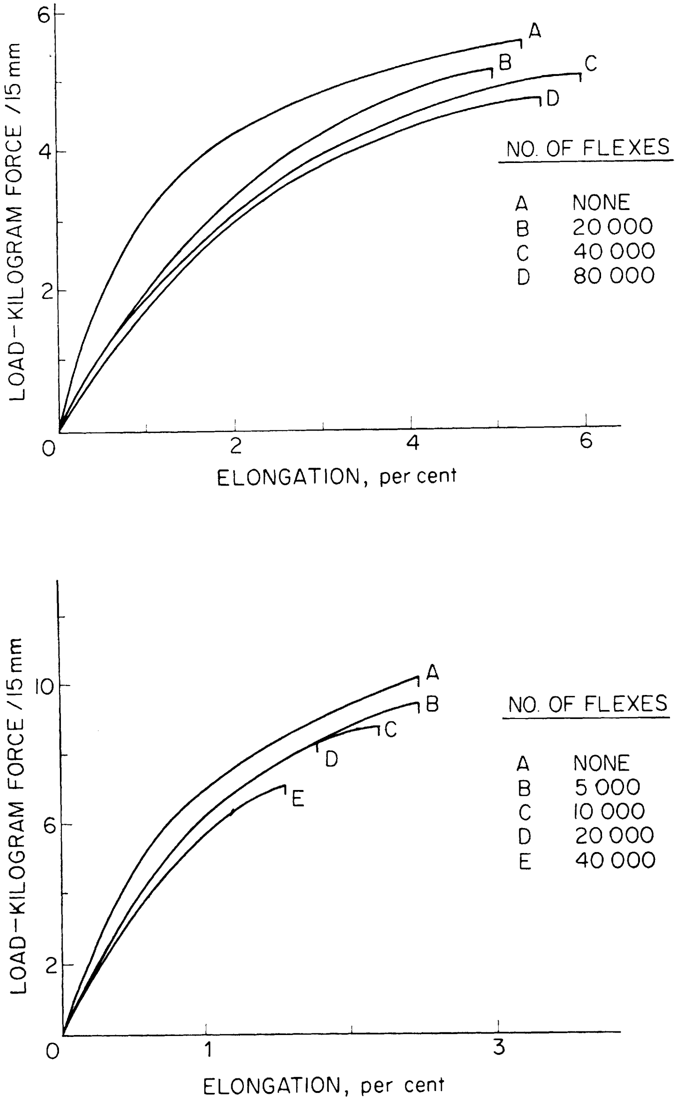

Fig. 9—Load/elongation curves for flexed cotton ledger paper

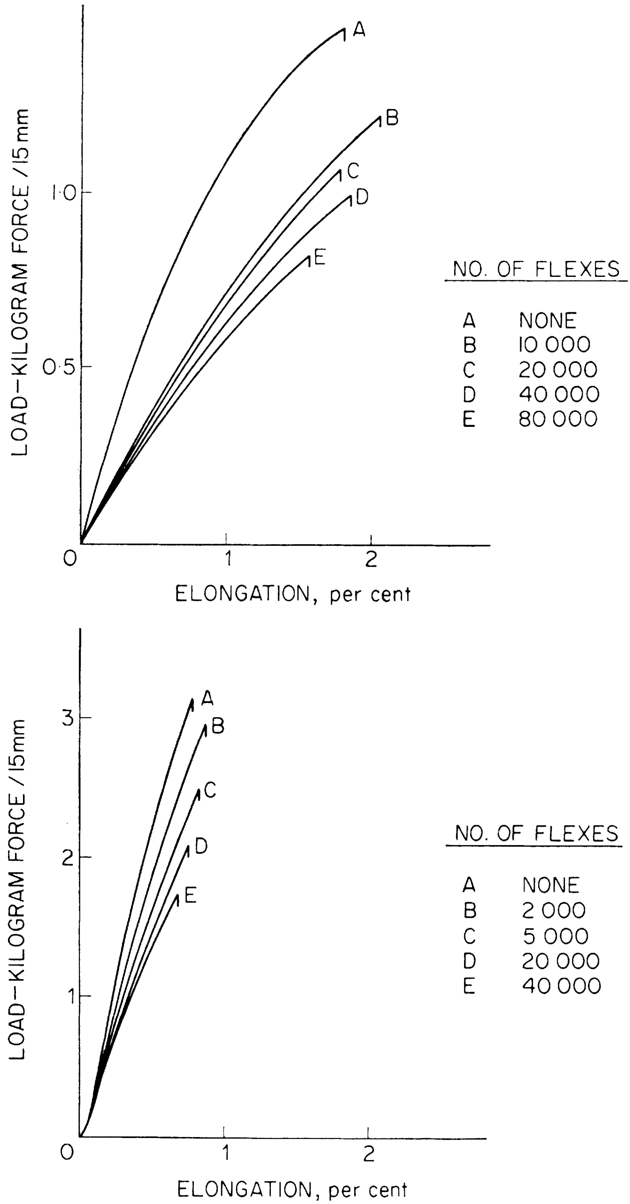

Fig. 10—Load/elongation curves for flexed newsprint

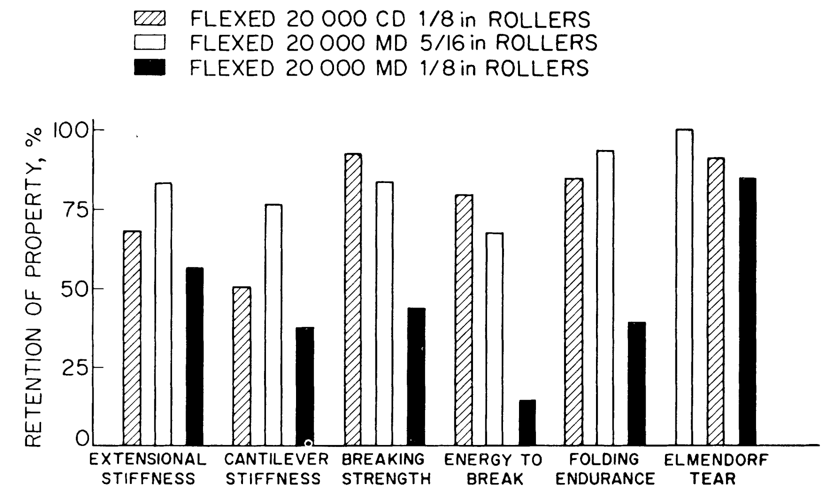

Fig. 11—Effect of strain level during flexing on the degradation of physical properties

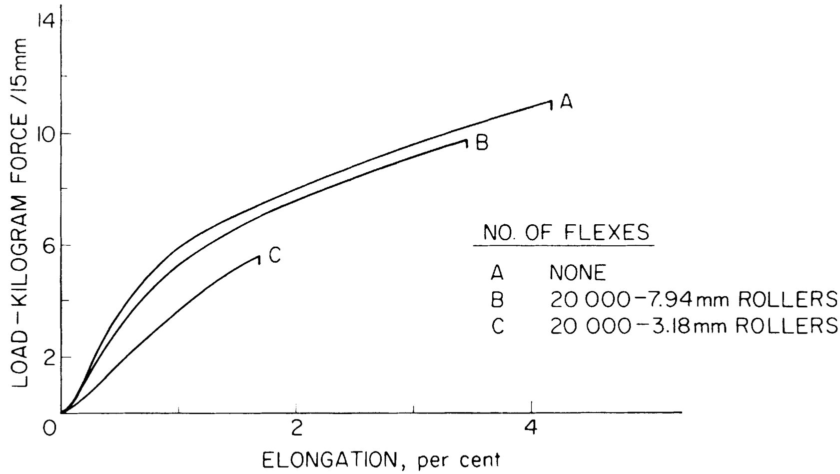

Fig. 12—Effect of roller size on the load/elongation properties of high grade rag paper when flexed in the MD

DISCUSSION

AS MENTIONED previously, there is a large increase in porosity as the modulus of paper decreases in the early part of the flexing cycle. It appeared that the structural changes occurring during flexing, which caused the porosity to increase, was also responsible for the decrease in modulus and cantilever stiffness. During the interval of rapid increase in air permeability and large decrease in modulus, little if any decrease in breaking strength occurs, which indicates that no bond breakage is occurring.

Scanning electron photomicrographs of paper (Fig. 13–15) indicate the presence of a film-like material in addition to the fibres. Upon examining the film-like material (or matrix), it appears to consist of small densely packed fibres, evidently produced during beating.

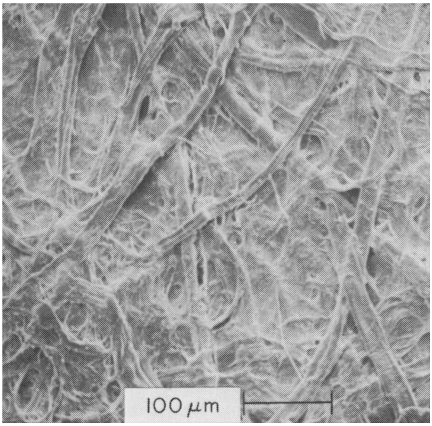

Fig. 13—High grade rag paper ×170

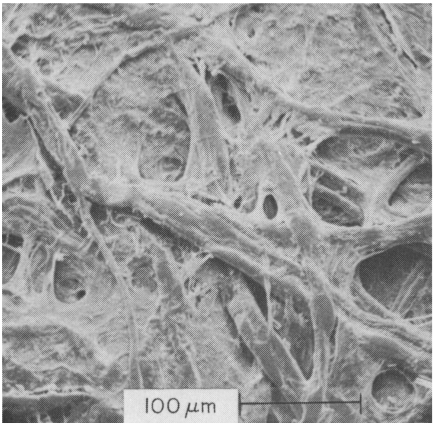

Fig. 14—All cotton ledger paper ×240

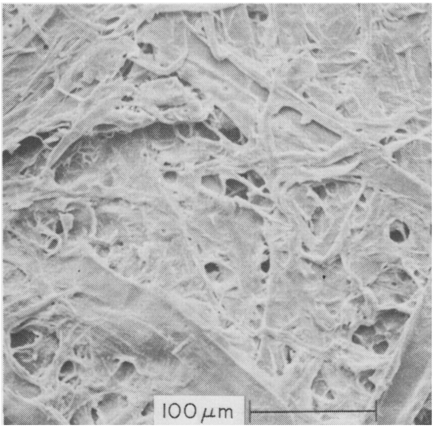

Fig. 15—Newsprint ×255

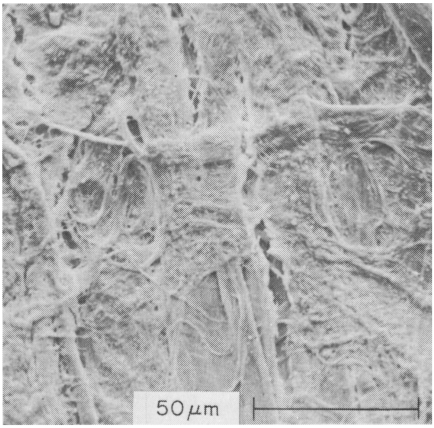

Fig. 16—High grade rag paper flexed 80 000 times in CD over 3·18 mm rollers: cracks are running parallel to MD ×650

The amount of matrix appears to be proportional to the air permeability of the paper. The high grade rag paper has a very low air permeability and a very high proportion of matrix constituent, whereas the cotton ledger paper has a much higher air permeability and a smaller proportion of matrix constituent (Fig. 13 & 14).

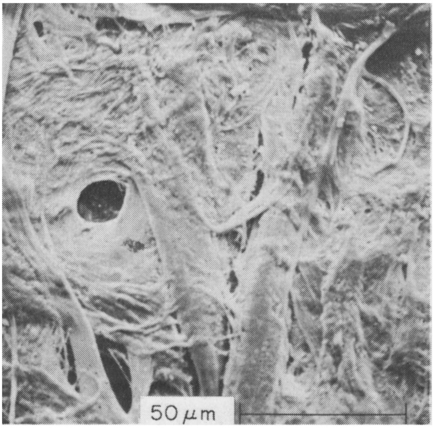

Fig. 17—All cotton ledger paper flexed 80 000 times in CD over 3·18 mm rollers: cracks are running parallel to MD ×660

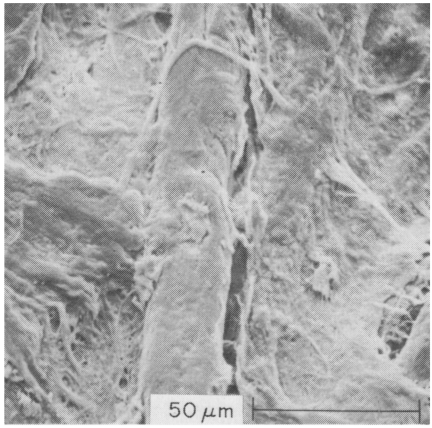

Fig. 18—Newsprint flexed 80 000 times in CD over 3·18 mm rollers: cracks are running parallel to MD ×660

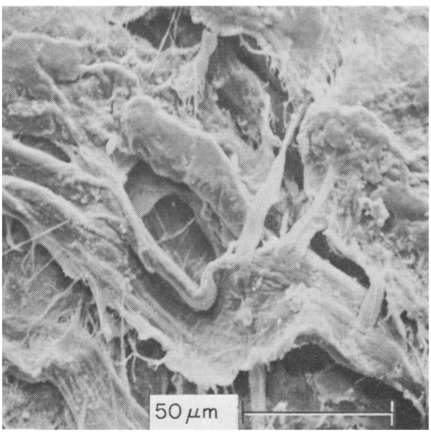

Fig. 19—Delamination in all cotton ledger paper flexed 80 000 times over 3·18 mm rollers ×595

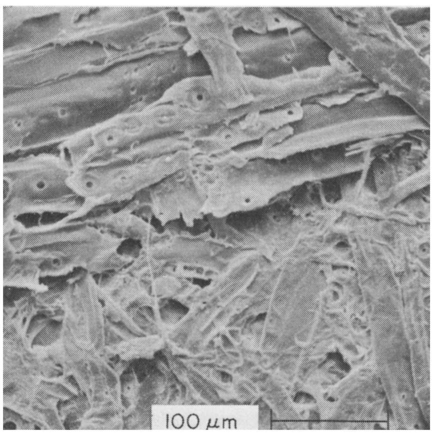

Fig. 20—Delamination in newsprint flexed 80 000 times over 3·18 mm rollers ×225

Cracks develop in this film-like material during flexing, which accounts for the increase in porosity (Fig. 16–18). In some instances, such as with ledger and newsprint papers, fibre delamination occurs in addition to matrix cracking (Fig. 19 & 20). In these instances, it would be expected that the porosity increase would be higher than in cases of matrix cracking alone.

The matrix spans the areas between the fibres and this causes a shortening of the effective fibre segment length. This also decreases the fibres' ability to move laterally or to twist when the paper is strained. The shortening of the fibre segments leads to an increase in bending stiffness, as the apparent fibre stiffness increases as the fibre length decreases. The constraint of fibre twisting and lateral movement causes the paper to be more difficult to deform. Consequently, a greater force will be necessary to strain paper a given amount, with the result that the initial slope of the load/elongation curve will be greater than in a situation in which the fibres are free to twist and move laterally. When the matrix deteriorates, as in crack formation during flexing, the constraints of fibre movement are reduced and the effective fibre segment length increases. Deformations thus occur more easily when the paper is strained and the initial slope of the load/elongation curve decreases. The increased fibre segment length results in a lower fibre stiffness and the bending stiffness decreases. If no interfibre bonds are broken at the time of matrix cracking, no decrease in strength is observed, even though a large decrease in modulus occurs.

It has been observed that cracking of the matrix usually occurs at right-angles to the direction of strain during flexing. Consequently, the change in rheological properties can be expected to occur primarily in the direction the paper was flexed. Since some cracking occurs in the opposite direction (Fig. 21), some change in the rheological properties can be expected in the direction opposite to the direction of flexure.

When fibre delamination occurs in addition to matrix cracking, an appreciable change in rheological properties can be expected to occur in both directions. SEM photomicrographs revealed a substantial amount of fibre delamination in both ledger and newsprint papers flexed in the CD, but not in the high grade rag paper. As a consequence, when the papers were flexed in the CD, the decrease in tensile properties in the MD was greater for the ledger and newsprint papers than for the high grade rag paper.

Cracks similar to those found in flexed paper have been observed in documents printed on high quality rag paper which received considerable handling (Fig. 22).

It would appear that the matrix contributes significantly to the modulus and bending stiffness of paper. As the amount of matrix increases with beating, so does the modulus and stiffness. It would also appear that modification of the matrix would result in significant changes in paper properties without affecting strength. In fact, there is a good possibility that some paper converting processes, such as saturation with synthetic latices, beater addition of synthetic latices and the mere addition of plasticisers, have produced important new paper products because of matrix modification.

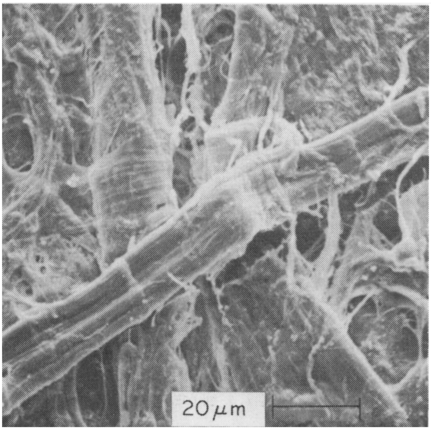

Fig. 21—Cracks running in both CD and MD after flexing in CD over 3·18 mm rollers ×860

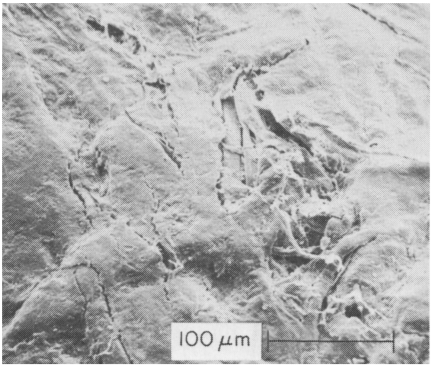

Fig. 22—Cracks found in a document printed on a high grade rag paper that received considerable handling ×250

Although the high grade rag is the most durable of the three papers investigates, its retention of physical properties was not always the highest of the three papers. What must be considered here is the superiority of the initial physical properties of the high grade rag compared with the other two papers. The high grade rag paper can deteriorate substantially and still have properties superior to either of the other papers. In fact, the superior durability of the high grade rag paper is probably due to the paper having adquate physical properties after considerable use, not to the low rate at which the properties deteriorated.

Data on the high grade rag indicate that a paper having substantially greater physical properties than required for a particular use has a good chance of enduring considerable handling over an extended period of time. Unfortunately, this may not be the most economical procedure to follow.

CONCLUSIONS

1. The flexing test described appears to be a suitable method for evaluating the relative durability of papers. As each property may deteriorate at a rate independent of other properties, it would be necessary to specify the important properties, then determine the rate and extent of decline during flexing between two or more papers.

2. Paper appears to bear some resemblance to a fibre-reinforced plastic, at least from a visual standpoint. The matrix apparently consists of a film-like portion produced during the beating of the pulp and seems to have a significant effect on the bending stiffness and elastic modulus.

3. When paper is flexed, as it is in document handling, the matrix cracks, air permeability increases and the modulus and bending stiffness decline, primarily in the direction of flexing. As some matrix cracking occurs parallel to the direction of flexing, some deterioration of properties occurs in the direction opposite to flexing, but to a lesser degree.

4. At times, interfibre debonding occurs during flexing, resulting in substantial deterioration of most physical properties in both directions of paper. Bending to high degrees of strain are more likely to cause interfibre debonding.

5. In general, the decline of physical properties is greatest when paper is flexed in the MD, especially at high levels of strain (small radius of curvature). As few, if any, restrictions are made on the extent to which paper is flexed during handling, it would seem logical for paper documents to be designed so that the direction flexed most during handling is in the CD of the paper.

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Discussion

Dr K. Ebeling I would like to congratulate Dr Graminski on an excellent presentation. It seems to me that here we have direct experimental evidence for the mechanisms proposed in my paper to account for the dissipation of energy during the straining of paper. May I add that we should not look at fibre-to-fibre bonds alone. We should not forget the bulk of the cell wall. Similar phenomena are taking place there between the fibrils and the lamellae.

Dr N. K. Bridge Although many of us are interested in this paper because of its theoretical points of view, there is a practical point to question. I find it inconceivable that banknotes receive the amount of flexing you appear to be giving them in your test—something like 20 000 flexes, which is ten times a day for several years!

Dr E. Graminski The number of flexes reported in this paper are more than necessary to determine durability. We have revised our flexing procedures. At the time that this work was started, we were unsure what the flexing procedure should be or what factors were important, so we flexed the paper for a long time. We find that as few as a thousand flexes or less than 10 min of flexing is all that is required to estimate durability.

Dr A. B. Truman This reminds me of some work done in 1963* when we were looking for a similar effect. We used the technique that Derek Page had developed for detecting and measuring the size of fibre-to-fibre bonds. We passed strips of paper at constant load over a sharp edge, we followed the pattern of the breakage of bonds and we tried to quantify it. Your results support our findings on structural change.

Dr D. H. Page In your apparatus, I think it is rather important whether or not the paper at the inner side of the flexing cylinder is going into compression or is still in tension. If it goes into compression (and can you calculate this?), there is opportunity for micro-compressions to be produced in the

* Jackson, M. and Truman, A.B., *Paper Tech.*, 1965, **6**(3), T45–T51

Under the chairmanship of Dr H. G. Higgins fibres and that would lower the modulus of the paper. Do you get different results at different tensions?

Dr Graminski We have performed experiments in which the restraining force was varied from 400 g to 1 000 g and found no significant difference in the results. The side facing the rollers may go into compression, but you must remember that, as flexing proceeds, the side in compression eventually goes into tension and vice versa. It is unlikely that micro-compressions account for the decline in modulus, since papers that exhibit good stiffness and modulus retentions do not exhibit a large increase in air permeability. There is an excellent correlation between decline in stiffness and increase in air permeability. We have not calculated whether the paper facing the roller goes into compression.

Dr J. Grant There is a very important factor determining the durability of papers that have to be bound in books (and you were talking about ledger papers)—the way in which the sheets are bound up. Theoretically, in order to get the maximum durability for a bound book and the sheets contained in it, it should be bound up with the machine-direction running across the double page. In practice, this is not done, because the binders do not like it; you cannot open the book flat. If you open it in the centre, the pages will not stay open. Consequently, the machine-direction usually runs down the sheet, which of course makes the paper weak at the fold of the double page. If it is possible to devise a paper that would open flat, the book could be bound up with the machine-direction running across the book instead of down. The durability of bound ledgers would thus be increased tremendously and the increase would far transcend anything that can be done on the papermaking side, including the effect of flexing resistance.

Dr Graminski In designing documents, it would be advantageous for the cross-direction of the paper to run in the direction that will receive the most flexing. It is the cross-direction of paper that retains its properties most during flexing.

Mr J. R. Parker May I comment on the possible effects of thickness. I assume that the paper, as it passes round the rollers, conforms closely to their curvature. The strain variation at the paper surface during the test will therefore be proportional to the paper thickness. Have the effects of this been observed? In addition, what were the thicknesses of the paper samples for which the results have been presented?

Dr Graminski I am sorry that the thickness values were not included in the preprint. They were 3·8 thousandths of an inch for the newsprint, 4·2 for the ledger paper and 4·8 for the high grade rag paper. Presumably, the thickness of paper will have a bearing on the results, but we have not investigated this factor specifically.

Mr Parker May I suggest an experiment? If papers of different thicknesses were used, then the excursion of the strain could be varied in relation to the radius of bending, so that the effect of flexing (which might cause stiff fibres and shives to break away from the paper surface) could be distinguished from the effects of strain in the test direction.

Dr Graminski Yes, this could be done. In fact, I have observed that, when interfibre debonding occurs as a result of flexing, there is a larger decline in physical properties in the direction opposite to flexing than when little or no interfibre debonding takes place.

Dr C. T. J. Dodson Did you observe partial failure of fibre-to-fibre bonds? Have you also investigated an effect of moisture? If so, did you see cracks in the matrix at higher moisture contents?

Dr Graminski We did not flex at high humidity conditions, but the conditions in the test room had gone down accidentally to a very low humidity one winter's day and the matrix deteriorated severely. Yes, moisture has a definite effect.