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SOME FURTHER CONSIDERATIONS ON COMPONENT EDGEWISE COMPRESSION TESTING

Project 1108-4

A Preliminary Report

to

TECHNICAL COMMITTEE
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SUMMARY

A comparison of modified ring compression, regular ring compression and the Concora Liner Test (CLT) was made for the cross direction of twenty samples of fourdrinier kraft linerboard spanning a wide range of basis weights and tested in a Hinde and Dauch compression testing machine. Among the conclusions reached were the following:

1. The modified ring compression strength exceeded the regular ring strength by 18.0%, on the average, which follows the trend of earlier studies.

2. The CLT strength was less than the regular ring strength by 39.1% on the average.

3. The per cent difference between regular ring compression and CLT strength increased with decreasing basis weight.

4. The per cent difference between modified ring and regular ring compression was sensibly independent of basis weight, as was found in earlier work.

5. Regression equations are given for the relationship between (a) modified ring compression and CLT, and (b) regular ring compression and CLT.

Comparison of the ring compression test values obtained from the H. and D. tester and earlier values performed on the same samples by means of a modified Riehle tester highlighted the effect that the testing machine may have on compression test results. The following effects were noted:

6. The H. and D. compression tester gave higher test values than a modified Riehle tester, by about 3%, on the average, with modified ring specimens and 10% with regular ring specimens.

7. This difference between the two testing machines could not be explained satisfactorily from considerations of (a) platen parallelism, or (b) strain rate experienced by the specimen. A mechanical analysis of the two testing machines with respect to specimen strain rate is included in this report in the belief that it may be of general interest to personnel concerned with containerboard testing.

8. It is speculated that the cited difference between the two testing machines may involve the dynamic behavior of the weighing systems during the brief period in which the specimen fails.

9. The modified ring and regular ring compression strengths obtained with the H. and D. tester were highly correlated, substantiating an earlier result obtained with a modified Riehle tester. An allied study is directed to examining the correlation within a given linerboard machine, in view of the possible implications of the correlation to control testing.

It has been the practice in this laboratory to test liners by means of six-inch rings (modified or regular) and corrugating mediums by two-inch rings—the latter ring size to compensate for the lower flexural stiffness of mediums. It may be questioned whether lightweight liners (below 42-lb.) should also be tested as two-inch rings because of the diminishing flexural stiffness as liner weight decreases. A comparison of two-inch and six-inch modified ring strength was made on ten samples of liner ranging from 29 to 43 lb./1000 sq. ft. in basis weight. The following conclusions were drawn from this study:

10. A modest increase in indicated strength (about 3%, on the average) may be obtained with two-inch modified ring compression for liners having nominal basis weights of 33 lb./1000 sq. ft. and below. Although the preceding is based on weight of the board, a more appropriate criterion might be caliper.

11. Further study of this effect is being carried out. If the trend shown in the present work continues, it will be advisable to test lightweight liners (nominally 33 lb./1000 sq. ft. and below) as two-inch modified rings.

INTRODUCTION

Studies of top-to-bottom box compression behavior have revealed that the dominant material property is the cross-direction edgewise compression strength of the combined board (1). This property depends, in turn, upon the edgewise compression strength of the liners and medium. Considerable effort was made to develop an adequate edgewise compression test of components. This work resulted in the modified ring compression test, which is apparently more accurate than (although highly correlated with) the regular ring compression test (2).

The present study was undertaken to provide a comparison of the modified ring strength (and regular ring strength) with the Concora Liner Test (CLT). The latter test has been used extensively for a number of years in certain segments of the industry and purports to measure the same basic property of liners as do the ring-type tests.

A second objective was served by this work, namely, an examination of the effect of type of testing machine on the test results. It is well known that differences between testing machines can be a troublesome factor in interlaboratory comparisons of test properties. For example, differences between machines of a given type may be due to calibration errors—this being one of the reasons for the continuing base-line studies on liner and medium. Discrepancies also may arise between machines differing in construction and operation. For example, the latter effect is apparent in an intralaboratory instrumentation study at the Institute involving an H. and D. crush tester and a modified Riehle testing machine (3). (The modification of the Riehle tester was performed a number of years ago and involved replacing the original hydraulic system with a cantilever beam weighing system.)

The testing during development of the modified ring compression test in this laboratory was performed on a modified Riehle testing machine as a matter of convenience. The present work provided an opportunity to retest some of the same component materials by means of an H. and D. tester. The results may be of general interest inasmuch as the latter type of testing machine is used widely throughout the industry.

In connection with this comparison of the modified Riehle and H. and D. test results, a mechanical analysis of the two testers was performed with regard to the rate of strain induced in the test specimen. This analysis is included in an appendix to this report. It is believed that it may be of interest in other contexts in addition to the present considerations in view of the diverse uses of these types of testing machines in the container industry.

A third objective of this study was a comparison of six-inch and two-inch modified ring compression strength of lightweight liners. The shorter (i.e., higher curvature) ring specimen has been used for testing corrugating mediums to compensate for their low flexural stiffness. It may reasonably be questioned whether lightweight liners should be tested as two-inch rings for the same underlying reason.

MATERIALS

Twenty samples of fourdrinier kraft linerboard were selected from the materials of the commercial box study (1). The basis weight of the samples ranged from 33.8 to 95.0 lb./1000 sq. ft. Two of the samples were nominally 33-lb. liners; eight samples were nominally 42-lb.; seven samples were 69-lb.; and the remaining three samples ranged from 84 to 95 lb./1000 sq. ft. In addition to spanning the practical range of basis weights, the samples were selected so as to be free of curl, this being a troublesome condition when testing by the CLT method.

TEST PROCEDURE

Ten cross-direction compression specimens were prepared from each sample for each type of test (modified ring, regular ring, and CLT). The specimens were cut to 0.5 by 6.0 inches by means of a Concora strip cutter. The modified ring specimens were reinforced and joined as described in Reference (2).

All specimens were tested in an H. and D. compression testing machine. The initial parallelism of the platens (in the test specimen area) was maintained within ± 0.002 inch. The regular rings were tested by the ASTM method. The special islands for the modified ring specimens are described in Reference (2). A straightening device was not used with the CLT specimens although, as mentioned above, care was taken to select samples exhibiting no visible curl. One operator prepared all specimens and a second operator performed all of the testing.

DISCUSSION OF RESULTS

COMPARISON OF THREE LINER COMPRESSION TESTS

The average test values of modified ring and regular ring compression and CLT for each sample are shown in Table I along with the basis weight and caliper of the sample. Compression strength is in units of pounds per inch of width, that is, specimen load divided by six inches. Per cent differences between test methods, based on regular ring compression, are also shown in the table.

It may be seen that in all instances the modified ring compression strength was higher than the regular ring strength. The average difference was +18.0%; individual differences ranged from +4.5 to +31.2%.

In all cases the CLT values were lower than the regular ring strengths. On the average, the difference was -39.1%, with individual differences ranging from -13.7 to -56.5%.

An alternate statement of these results is that the CLT strength was 48.4% lower than the modified ring strength, on the average. Or, the modified ring strength was 93.7% higher than the CLT.

It may be seen in Table I that the difference between CLT and regular ring compression varied with basis weight, being highest for lightweight liners (42-lb. and below) and diminishing as the basis weight increased. As shown in Table I, the average difference was -53.8% for 42-lb. liners and below, while the average difference was -24.4% for 69-lb. liners and above. This trend may be attributed to the relationship between flexural stiffness and span of the CLT specimen. As the basis weight decreases the flexural stiffness of the specimen also decreases and the specimen bends and buckles more readily. In contrast, the ring specimen is much more stable because of its circular configuration.

TABLE I

CROSS-MACHINE EDGEWISE COMPRESSION STRENGTH OF LINERS

Code No.	Basis Weight, lb./1000 sq.ft.	Caliper, pt.	Compression Strength, lb./in.[a] Modified Ring	Diff., %[b]	Regular Ring	CLT	Diff., %[b]
1196	33.8	9.2	13.3	+23.1	10.8	4.7	-56.5
2168	34.3	10.0	12.5	+26.3	9.9	4.4	-55.6
2220	41.3	11.8	15.7	+30.8	12.0	5.5	-54.2
1189	41.8	11.9	15.8	+26.4	12.5	6.0	-52.0
1148	42.5	12.8	16.8	+21.7	13.8	6.6	-52.2
1164	42.6	12.5	16.1	+11.8	14.4	6.8	-52.8
2147	42.6	12.8	17.4	+17.6	14.8	6.8	-54.1
1175	42.8	12.2	17.1	+14.0	15.0	6.8	-54.7
1194	42.8	13.3	16.5	+13.0	14.6	6.9	-52.7
2210	43.0	12.0	17.3	+ 8.1	16.0	7.5	-53.1
			Av.	+19.3		Av.	-53.8
2249	68.4	22.1	27.4	+21.8	22.5	16.4	-27.1
2053	69.0	22.3	28.8	+20.0	24.0	19.6	-18.3
2034	69.2	20.5	27.6	+ 4.5	26.4	17.6	-33.3
2160	70.1	21.1	30.2	+15.3	26.2	19.3	-26.3
2185	70.4	20.6	29.6	+12.1	26.4	17.4	-34.1
2370	70.9	22.0	24.6	+25.5	19.6	15.5	-20.9
2251	71.0	21.9	26.9	+31.2	20.5	14.3	-30.2
2140	84.1	24.6	31.4	+13.4	27.7	21.6	-22.0
2158	91.1	27.1	34.3	+ 9.6	31.3	25.6	-18.2
2089	95.0	26.4	35.7	+14.1	31.3	27.0	-13.7
			Av.	+16.8		Av.	-24.4
			Composite Av.	+18.0			-39.1

[a]Testing done on an H. and D. (L-1309) test machine.

[b]Based on regular ring.

On the other hand, there is very little trend for the per cent difference between modified ring and regular ring strength to vary systematically with liner weight [an observation noted in Reference (2)]. Apparently, the weakness of the regular ring specimen at the loading edges and at the free ends depreciates the strength of the specimen by a per cent that is independent of the basis weight. With regard to the comparison of regular and modified ring compression, it may be recalled (2) that the reinforcement given to the modified ring specimen introduced extraneous load in an amount less than 1% of the test value; thus, it is a matter of the regular ring strength being less than the true strength of the liner, rather than the modified ring strength being higher than the true strength.

It may be of interest to examine more closely the relationship between modified ring compression strength and CLT, inasmuch as considerable test experience with the latter may have been accumulated over the years in some laboratories. A graph of the modified ring strength vs. CLT for the twenty samples studied is given in Fig. 1. The graph also shows regular ring strength vs. CLT, for the sake of completeness. These data are also shown in log-log co-ordinates in Fig. 2; this choice of co-ordinates is appropriate for relating the tests by means of a power function.

Regression analyses were performed for these several cases (modified ring strength vs. CLT and regular ring strength vs. CLT). Both linear and power functions were fitted to the data. The results are summarized in Table II which shows the regression equation, the correlation coefficient, the average difference between observed and predicted ring strength, and the distribution of differences within several per cent intervals. A tabulation of individual differences (that is, for each sample) is given in Table III.

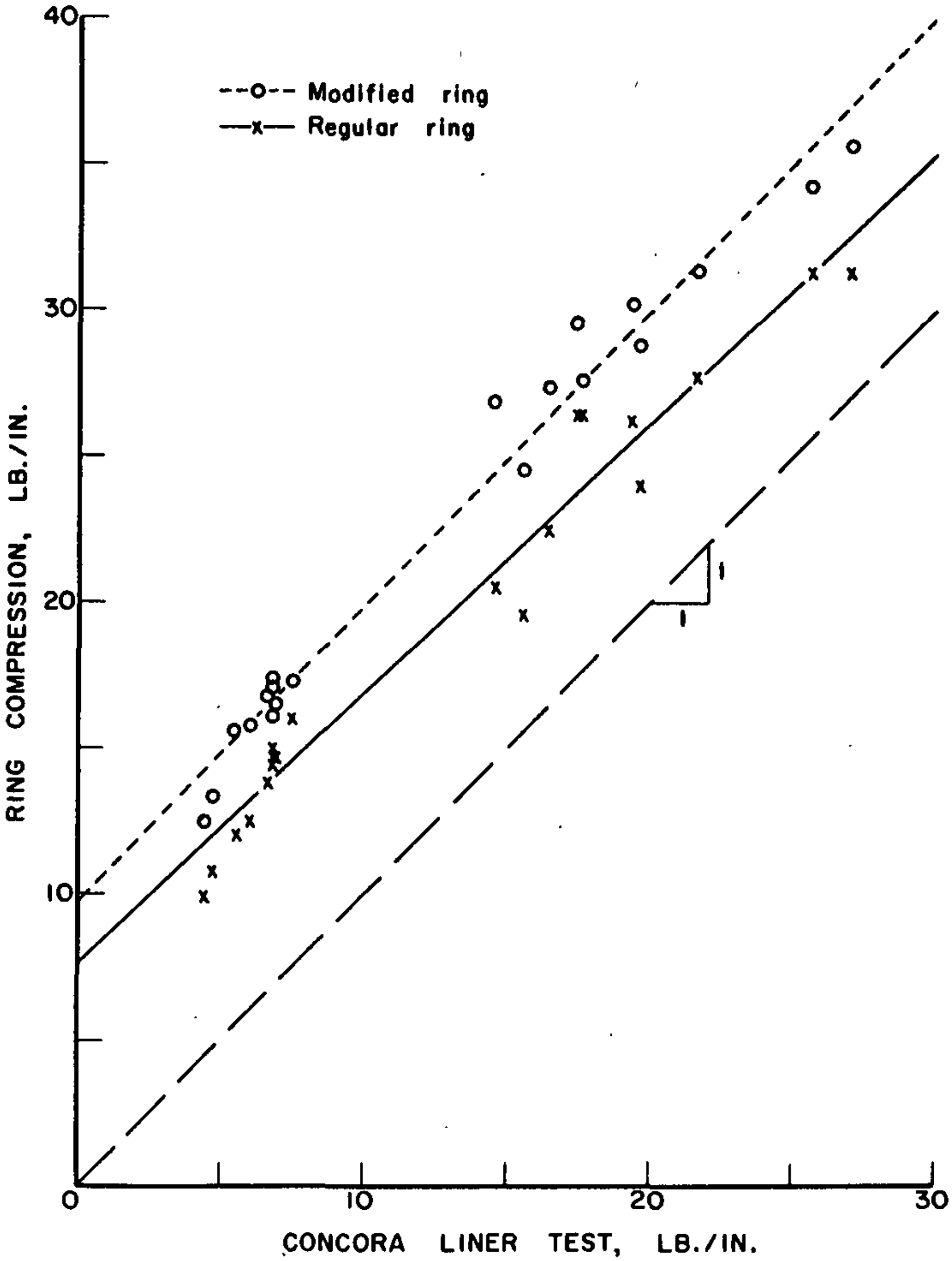

Figure 1. Relationship Between Cross-Direction Ring Compression Tests and Concora Liner Test (CLT) in Linear Co-ordinates

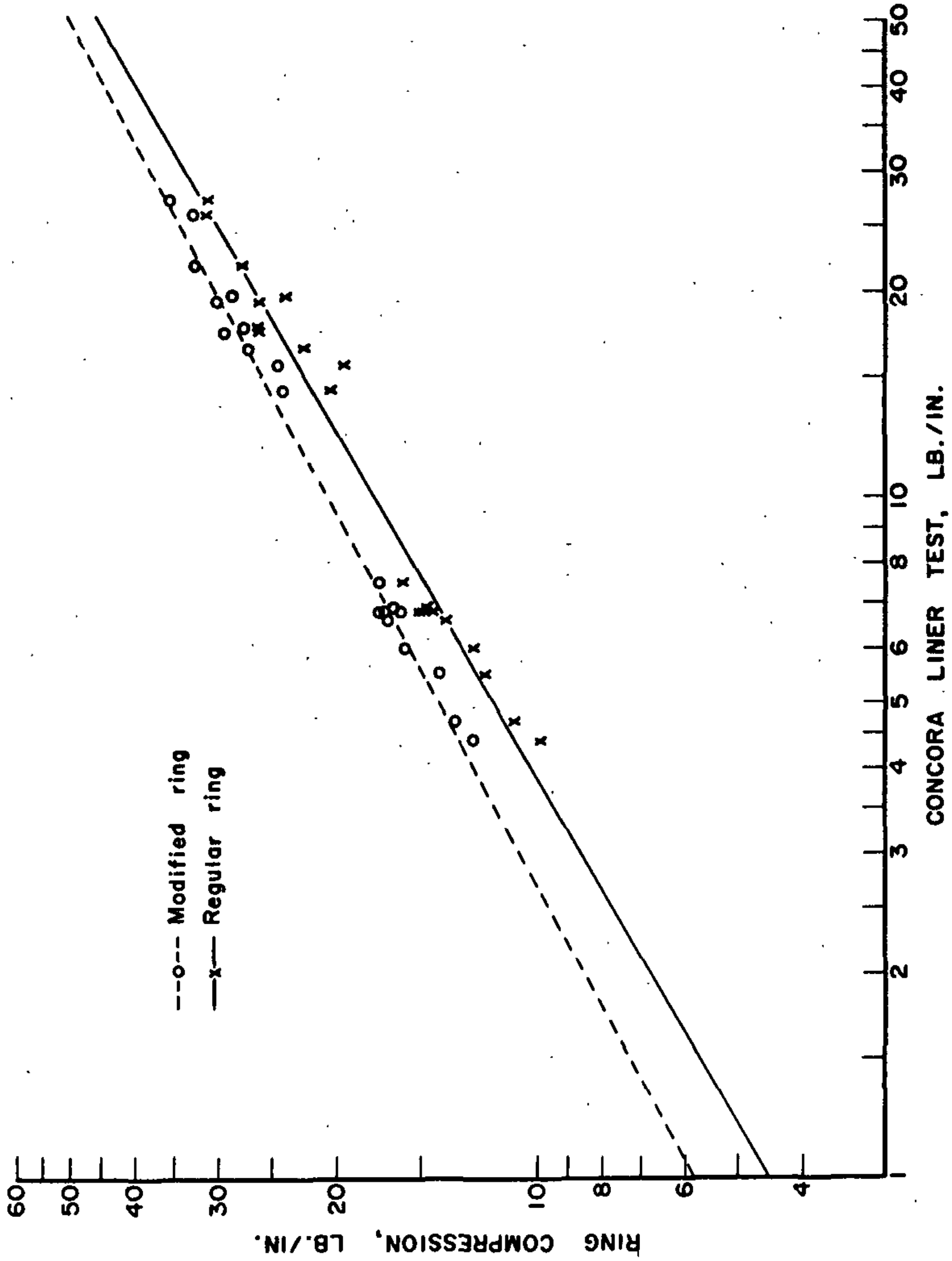

Figure 2. Relationship Between Cross-Direction Ring Compression Tests and Concora Liner Test (CLT) in Logarithmic Co-ordinates

TABLE II

RESULTS OF REGRESSION ANALYSES

Equation	Correlation Coefficient	Average Diff., %	Per Cent of Comparisons Within ± 5%	± 10%	± 15%	± 20%
Modified Ring Compression (*y*) vs. CLT (*x*)						
$y = 1.01x + 9.85$	0.988	4.0	80	95	100	100
$y = 5.81x^{0.551}$	0.994	3.0	75	100	100	100
Regular Ring Compression (*y*) vs. CLT (*x*)						
$y = 0.92x + 7.64$	0.981	6.0	45	80	95	100
$y = 4.50x^{0.589}$	0.985	5.1	55	95	95	100

TABLE III

COMPARISON OF OBSERVED AND PREDICTED RING COMPRESSION STRENGTH BASED ON CLT STRENGTH

Code No.	Basis Weight, lb./1000 sq.ft.	Caliper, pt.	Compression Strength, lb./in. Observed	Linear Equation	Diff., %[a]	Power Function	Diff., %
			Modified Ring Compression				
1196	33.8	9.2	13.3	14.6	+ 9.6	13.6	+ 2.5
2168	34.3	10.0	12.5	14.3	+14.2	13.1	+ 5.2
2220	41.3	11.8	15.7	15.4	- 2.0	14.9	- 5.3
1189	41.8	11.9	15.8	15.9	+ 0.6	15.6	- 1.3
1148	42.5	12.8	16.8	16.5	- 1.8	16.4	- 2.2
1164	42.6	12.5	16.1	16.7	+ 3.7	16.7	+ 3.8
2147	42.6	12.8	17.4	16.7	- 4.1	16.7	- 4.0
1175	42.8	12.2	17.1	16.7	- 2.4	16.7	- 2.3
1194	42.8	13.3	16.5	16.8	+ 1.8	16.8	+ 2.1
2210	43.0	12.0	17.3	17.4	+ 0.6	17.6	+ 2.0
2249	68.4	22.0	27.4	26.4	- 3.8	27.1	- 0.9
2053	69.0	22.3	28.8	29.6	+ 2.7	29.9	+ 4.0
2034	69.2	20.5	27.6	27.6	- 0.1	28.2	+ 2.3
2160	70.1	21.1	30.2	29.3	- 3.1	29.7	- 1.7
2185	70.4	20.6	29.6	27.4	- 7.5	28.0	- 5.3
2370	70.9	22.0	24.6	25.5	+ 3.5	26.3	+ 7.0
2251	71.0	21.9	26.9	24.2	- 9.9	25.2	- 6.4
2140	84.1	24.6	31.4	31.6	+ 0.6	31.6	+ 0.6
2158	91.1	27.1	34.3	35.6	+ 3.8	34.7	+ 1.1
2089	95.0	26.4	35.7	37.0	+ 3.7	35.7	0.0
				Av.	4.0		3.0
			Regular Ring Compression				
1196	33.8	9.2	10.8	12.0	+10.9	11.2	+ 3.8
2168	34.3	10.0	9.9	11.7	+18.2	10.8	+ 8.9
2220	41.3	11.8	12.0	12.7	+ 6.0	12.3	+ 2.5
1189	41.8	11.9	12.5	13.2	+ 5.5	12.9	+ 3.6
1148	42.5	12.8	13.8	13.7	- 0.4	13.7	- 0.8
1164	42.6	12.5	14.4	13.9	- 3.3	13.9	- 3.2
2147	42.6	12.8	14.8	13.9	- 5.9	13.9	- 5.8
1175	42.8	12.2	15.0	13.9	- 7.2	13.9	- 7.1
1194	42.8	13.3	14.6	14.0	- 4.0	14.1	- 3.7
2210	43.0	12.0	16.0	14.6	- 8.9	14.8	- 7.7
2249	68.4	22.0	22.5	22.8	+ 1.3	23.4	+ 4.1
2053	69.0	22.3	24.0	25.8	+ 7.3	26.0	+ 8.4
2034	69.2	20.5	26.4	23.9	- 9.4	24.4	- 7.5
2160	70.1	21.1	26.2	25.5	- 2.7	25.8	- 1.6
2185	70.4	20.6	26.4	23.7	-10.1	24.2	- 8.2
2370	70.9	22.0	19.6	22.0	+12.1	22.6	+15.6
2251	71.0	21.9	20.5	20.9	+ 1.7	21.6	+ 5.4
2140	84.1	24.6	27.7	27.6	- 0.3	27.5	- 0.6
2158	91.1	27.1	31.3	31.3	0.0	30.4	- 2.7
2089	95.0	26.4	31.3	32.6	+ 4.2	31.4	+ 0.4
				Av.	6.0		5.1

[a]Based on observed.

Table II shows that the power functions gave somewhat better fit than the linear equations. With modified ring strength as a function of CLT, for example, the average difference was 3.0%, while the corresponding average with the linear equation was 4.0%. Inspection of Fig. 1 reveals that the data points fall off from a straight line at the lowest basis weights; it is for this reason, primarily, that the power function gives the better fit because it comes closer to picking up these two points than does the linear equation.

Two differing viewpoints may be taken on this matter. One is that a curve of best fit should curve in to the origin of the graph (as the power function does) because if there is "zero" CLT strength, there should also be zero strength by another compression test, and not 10 lb./in. as given by the linear equation. On the other hand, there is the possibility that the two lightest-weight liners should be tested by means of two-inch rings (as with corrugating mediums) and that the six-inch ring strengths for these lightweight samples may be on the low side due to having too great a radius of curvature in the specimen relative to the flexural stiffness of the material. This latter possibility is treated later in this report.

Omitting the two lightest weight liners, both types of equations give about equally good fit, as shown in Table III. Specifically, the average difference for the remaining eighteen samples is 3.1% for the linear equation, and 2.9% for the power function (modified ring compression based on CLT). In the case of regular ring strength, the corresponding average differences are 5.0 and 4.9% for the eighteen samples.

There is a suggestion in the plotted points that the <u>regular</u> ring <u>vs.</u> CLT data for the 42-lb. liners (and below) might be described by a straight line of steeper slope than that of the heavier weight liners. Further attention might well be given to this possibility if interest warrants.

EFFECT OF TESTING MACHINE ON RING COMPRESSION TESTS

The twenty samples of liner tested in the H. and D. testing machine in the present study had been evaluated for modified ring and regular ring strength a year or so earlier in a modified Riehle compression tester. A comparison of the test results from the two testing machines is given in Table IV.

It may be seen that, on the average, the H. and D. values of modified ring compression were 3.3% higher than the modified Riehle loads. A greater difference occurred with regular ring compression; on the average, the H. and D. loads were 10.1% higher than the modified Riehle values. (Three extreme differences occurred with the regular ring specimens, in excess of 20%. These are being checked. It may be mentioned, however, that excluding these three differences still results in an average difference of 8% between testing machines.)

Several reasons may be advanced for these differences. On the one hand, there was a considerable period of time between the testing performed on the two machines—on the order of a year. However, the trends exhibited by the two machines have been observed in other intralaboratory studies where testing was performed on the same day with both machines. It is believed that the present results are probably not solely attributable to time effects, such as aging of the materials or inadvertent changes in operator technique and test methods. Moreover, the samples were stored in a conditioned atmosphere from the time of receipt and, therefore, would not be subject to changes in strength due to humidity cycling. It may be appropriate, therefore, to examine the mechanical characteristics of the two testing machines.

TABLE IV

EFFECT OF TESTING MACHINE ON MODIFIED RING AND REGULAR RING COMPRESSION STRENGTH

			Compression Strength, lb./in.					
			Modified Ring			Regular Ring		
Code No.	Basis Weight, lb./1000 sq.ft.	Caliper, pt.	Mod. Riehle	H&D	Diff., %[a]	Mod. Riehle	H&D	Diff., %[a]
1196	33.8	9.2	12.4	13.3	+ 7.2	9.6	10.8	+12.5
2168	34.3	10.0	11.0	12.5	+13.6	8.8	9.9	+12.5
2220	41.3	11.8	15.5	15.7	+ 1.3	11.7	12.0	+ 2.6
1148	42.5	12.8	16.2	16.8	+ 3.7	12.7	13.8	+ 8.7
2147	42.6	12.8	17.0	17.4	+ 2.4	13.5	14.8	+ 9.6
1175	42.8	12.2	15.6	17.1	+ 9.6	12.9	15.0	+16.3
2249	68.4	22.1	27.8	27.4	- 1.4	21.2	22.5	+ 6.1
2053	69.0	22.3	30.3	28.8	- 5.0	23.8	24.0	+ 0.8
2160	70.1	21.1	30.1	30.2	+ 0.3	25.0	26.2	+ 4.8
2370	70.9	22.0	24.0	24.6	+ 2.5	18.1	19.6	+ 8.3
1189	41.8	11.9	14.6	15.8	+ 8.2	12.0	12.5	+ 4.2
1164	42.6	12.5	14.4	16.1	+11.8	11.9	14.4	+21.0
1194	42.8	13.3	15.6	16.5	+ 5.8	11.7	14.6	+24.8
2210	43.0	12.0	17.3	17.3	0.0	13.3	16.0	+20.3
2034	69.2	20.5	27.4	27.6	+ 0.7	23.2	26.4	+13.8
2185	70.4	20.6	27.1	29.6	+ 9.2	23.2	26.4	+13.8
2251	71.0	21.9	28.1	26.9	- 4.3	21.3	20.5	- 3.8
2140	84.1	24.6	30.5	31.4	+ 3.0	25.2	27.7	+ 9.9
2158	91.1	27.1	35.4	34.3	- 3.1	28.2	31.3	+11.0
2089	95.0	26.4	35.4	35.7	+ 0.8	29.8	31.3	+ 5.0
			Algebraic Av.		+ 3.3			+10.1

[a]Based on Riehle values.

Of the two specific machines employed in this study, the modified Riehle tester is believed to offer the better platen parallelism. The parallelism of the platens of this particular H. and D. tester at the outset of the test can be maintained within ± 0.0020 inch, while the corresponding figure for the Riehle tester is ± 0.0005 inch. However, the poorer platen parallelism of the H. and D. is in the wrong direction to explain the higher test loads achieved with the machine.

A second matter for comparison is the strain rate induced in the test specimen, because paperboard is a viscoelastic material and will exhibit higher strength, in general, as the strain rate increases. The rate of motion of the driven upper platen of the H. and D. tester (0.9 in./min.) is about 4.5 times faster than that of the modified Riehle tester (0.19 in./min.). The strain rate in the test specimen, however, is not proportional to the rate of platen motion because a portion of the motion is taken up by the weighing beam of the testing machine (a simple beam in the H. and D. and a cantilever in the modified Riehle tester). The stiffness of the beam in the H. and D. is only one-tenth that of the Riehle, and consequently much of the faster platen motion of the H. and D. goes into deflecting the weighing beam rather than as strain rate in the specimen. In either tester, the actual strain rate in the specimen depends upon the stiffness of the specimen as well as the stiffness of the weighing beam.

The strain rate for either tester may be analyzed with a high degree of confidence because each tester is in essence a simple spring in series with a second spring, namely, the specimen. The appendix to this report presents the mechanical analysis; the major results of the analysis are discussed in the following paragraphs.

Figure 3 is a graph of the deformation rate in the specimen (in./min.) as a function of specimen stiffness (load/deformation, lb./in.) for each testing machine. In either case, the specimen deformation rate decreases as the specimen stiffness increases. Thus, for a very stiff specimen (e.g., a steel specimen), virtually all of the platen motion is taken up by deflection of the weighing beam and, therefore, the deformation rate in the specimen is small. On the other hand, with a soft specimen (e.g., sponge rubber), the weighing beam deflects only slightly and the deformation rate in the specimen approaches the rate of travel of the upper platen.

Data given in Reference (4) indicate that the stiffness of a regular ring specimen of 42-lb. liner lies in the range of 13,000 to 18,000 lb./in. and 69-lb. liner in the range of 18,000 to 24,000 lb./in. It may be seen in Fig. 3 that in these ranges of specimen stiffness, the H. and D. deformation rate is slightly less than that of the modified Riehle, despite the high rate of platen motion of the H. and D.

The above-mentioned ranges of specimen stiffness pertain to the early portion of the test on the specimen. When the stress in the specimen exceeds the proportional limit, the specimen stiffness begins to decrease and continues to decrease up to failure (and thereafter, of course, decreases markedly). Near the end of the compression test, therefore, the appropriate point on the curves of Fig. 3 moves to the left. This behavior is also analyzed in the appendix to this report. Order of magnitude estimates place the effective stiffness of 42-lb. liner as low as 4,000 lb./in. near the end of the test, at which point the deformation rate in the H. and D. tester exceeds the modified Riehle rate by about 30%. It may also be noted that the stiffness of a regular ring specimen is probably less than that of the modified ring because of its weak loading edges.

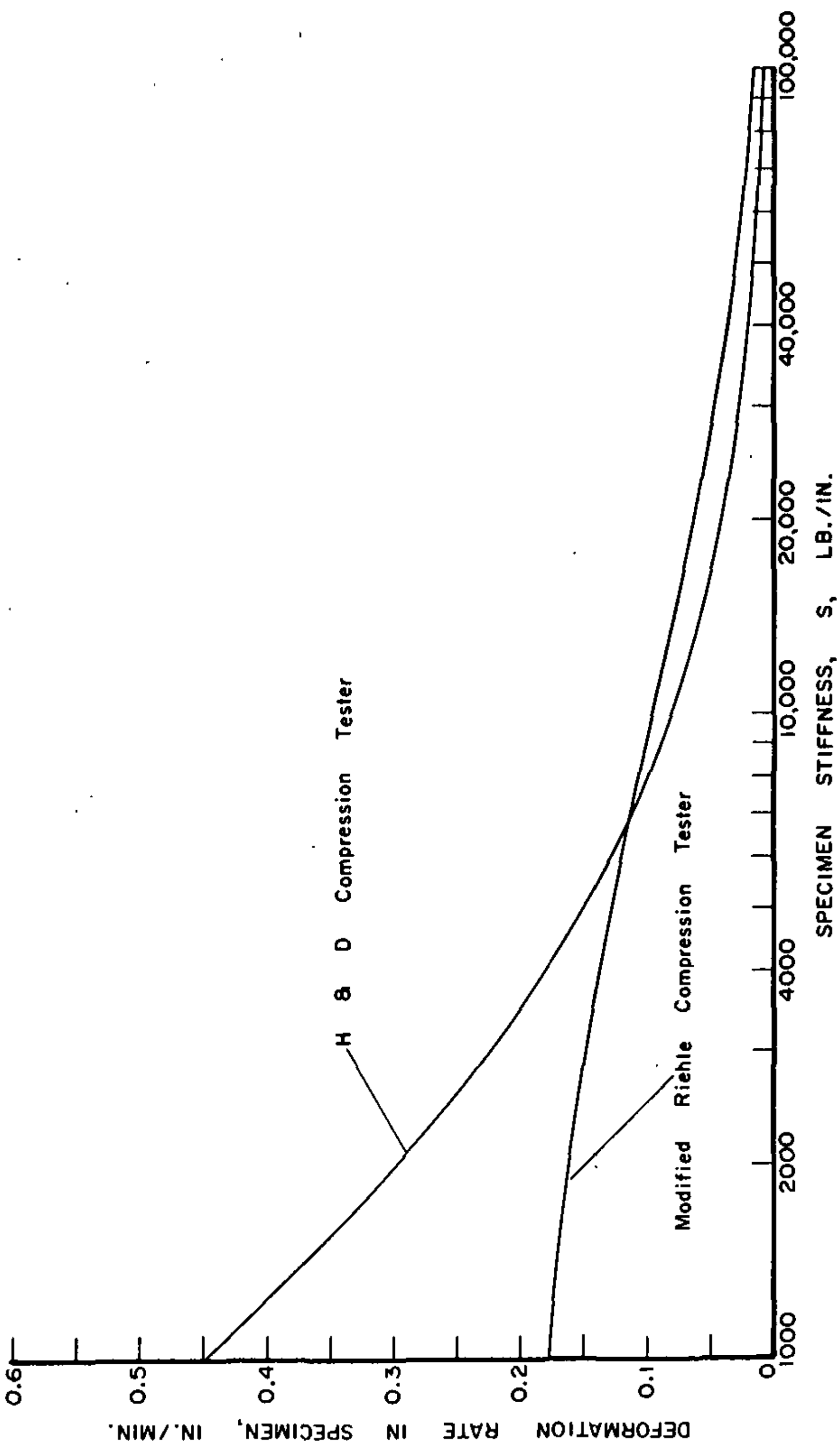

Figure 3. Relationship Between Rate of Deformation of a Specimen and Specimen Stiffness When Tested in a Hinde and Dauch Testing Machine and in a Modified Riehle Testing Machine

Interpretation of the effect of these differences in strain rate requires knowledge of the strength vs. strain rate characteristics of the specimen. There is, unfortunately, a scarcity of information on this point. As a guide to strain rate effects, Fig. 4 shows the effect of strain rate on the load vs. strain curve of a kraft paper in machine direction tension, as given by Andersson and Sjöberg (5). A cross-plot of tensile strength vs. strain rate revealed that tensile (T) was approximately related to strain rate ($\dot{\epsilon}$) by a simple power function [$T = 6.8\ \dot{\epsilon}^{(0.075)}$]. As a consequence, a tenfold increase in strain rate (anywhere within the range of the data) leads to a 19% increase in tensile; a fivefold rate increase gives 13% increase in tensile; and doubling the strain rate would be expected to increase the tensile strength by 5%.

Possibly as much as a doubling of strain rate (from modified Riehle to H. and D.) may be anticipated in the late stages of the ring compression test, as mentioned above. (The rates can never differ by more than a factor of 4.5 to 1.0, and this occurs only in a "zero" stiffness specimen.) However, it may be noted that the increase in tensile strength as a function of strain rate in Fig. 4 is apparently a cumulative effect from the beginning to the end of the test. It seems unlikely, for example, that a change from the lowest to the highest strain rate near the end of the tensile test would cause a jump from the lowest curve to the highest curve in Fig. 4. Thus, even if the tensile rate data of Fig. 4 were applicable to the compression test, it seems unlikely that a doubling of the strain rate near the end of the test could account for the 3 to 10% difference observed between the H. and D. and modified Riehle testers.

Another reason which has been suggested for the difference in indicated loads from the two testing machines concerns the behavior of the weighing beams during the failure process taking place within the specimen. That is, it is

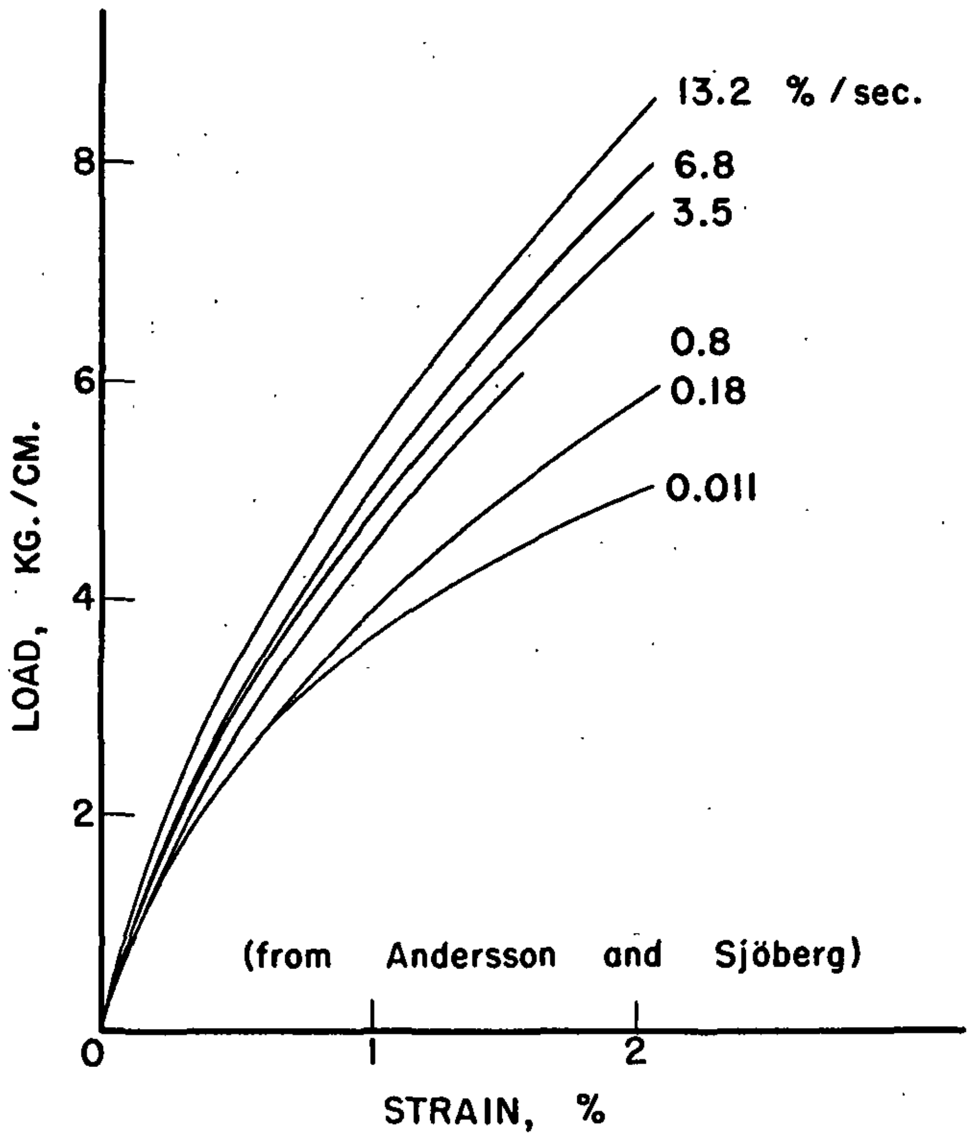

Figure 4. Effect of Strain Rate on Tensile Load-Elongation of a Kraft Paper in the Machine Direction [from Reference (5)]

visualized that when the specimen starts to fail (thereby suddenly reducing the over-all stiffness of the specimen) the stored energy momentarily imparts a negative acceleration (d^2u_b/dt^2) to the lower platen (the machines differ by a factor of 10 with regard to stored energy at a given load level—the H. and D. having the higher energy). The indicated load of the testing machine may exceed the true load on the specimen because of inertia effects during the negative acceleration of the weighing beam. This line of reasoning implies higher indicated load on the H. and D. than on the modified Riehle. A mechanical analysis of this effect has not been undertaken, however, and the arguments given above should be regarded only as speculative at this time.

By way of summary, there appears to be a real difference between the H. and D. and modified Riehle testing machines with respect to the ring compression values obtained. The difference cannot be explained by platen parallelism, and it seems unlikely, based on present information, that the difference is attributable to the differing deformation rates in the specimen. It is speculated that the source of the difference may lie in the differing dynamic responses of the weighing systems during the brief time that the specimen fails.

The effect of the differences in testing machine on the data of the present study is to narrow the spread between modified and regular ring strength. As shown in Table I, the modified ring strength exceeded the regular ring strength by 18%, on the average, whereas in previous work (2) the average difference for these same twenty samples was 25.5%. Although the H. and D. tester gave higher loads than the modified Riehle for both types of tests, the regular ring strengths increased more than the modified ring strengths (10.1 vs. 3.3%), as shown in Table IV, accounting thereby for the narrowing of the difference between the two types of ring tests.

In earlier work done with the modified Riehle tester (2), it was found that modified ring and regular ring strength were highly correlated. (This relationship may have utility in quality control and is being studied in an allied phase of this project.) Figure 5 shows the relationship between modified ring and regular ring compression obtained with the H. and D. tester in the present study. The solid line is the regression line for the twenty samples under study, and the dashed line is the regression line obtained in the earlier work with a much larger collection of samples (2). The major characteristics of the two analyses are summarized in Table V. It may be seen that while the constants of the regression equation change from the "old" to the "new" studies, the two types of ring tests performed on the H. and D. tester remain highly correlated over the range of basis weights studied. Allied studies are being directed to examining the correlation within a given linerboard machine.

TABLE V

CORRELATION BETWEEN MODIFIED RING AND REGULAR RING COMPRESSION STRENGTH

No. of Samples	Study	Test Machine	Equation	Correlation Coeff.	Av. Diff., %	Per Cent of Differences Within ±5%	±10%	±15%	±20%
125	Old	Modified Riehle	$y=1.19x+0.80$	0.988	3.7	74	96	100	100
20	New	H&D	$y=1.06x+2.00$	0.985	4.3	55	90	100	100

COMPARISON OF TWO- AND SIX-INCH RING TESTS ON LIGHTWEIGHT LINERS

Earlier studies have shown that the edgewise compression strength of corrugating mediums is determined more accurately by means of a two-inch perimeter ring compression specimen than by a six-inch specimen. This result may be attributed to the beneficial effect of the smaller radius of curvature of the two-inch

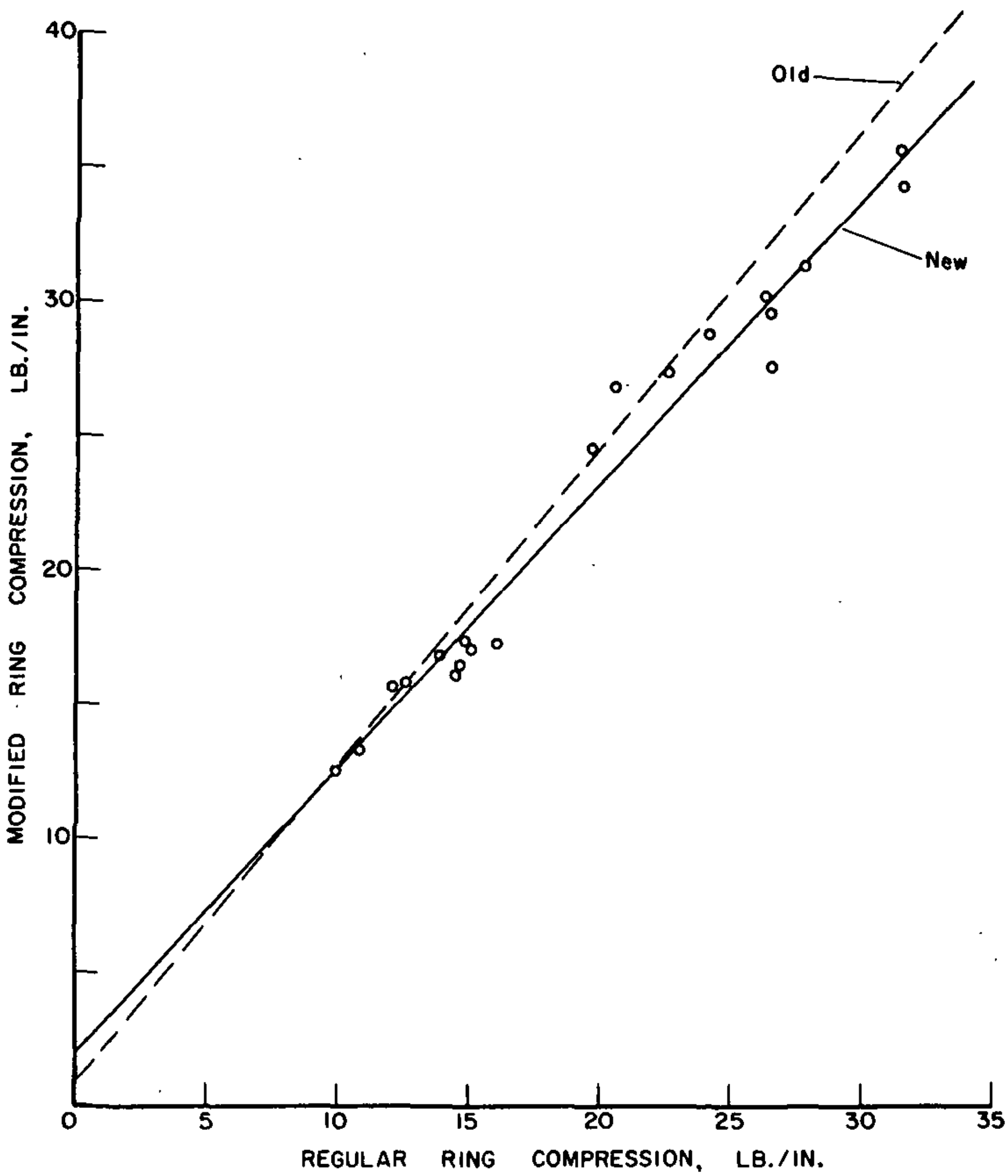

Figure 5. Relationship Between Modified Ring and Regular Ring Compression Strength (Cross-Direction)

ring in preventing buckling in the case of relatively flexible mediums. It has been the practice in this laboratory in recent years to test mediums as two-inch ring specimens and liners as six-inch rings.

It is reasonable to question whether a 26, 33, or 38-lb. liner should be tested as a two-inch ring or as a six-inch ring. While basis weight is probably not the best criterion for specifying ring size (flexural stiffness or caliper are probably more pertinent), it would appear likely that lightweight liners possibly may benefit from a smaller ring size. In connection with Table I and Fig. 1 earlier in this report, there was a suggestion that the six-inch ring strength of two 33-lb. liners might possibly be on the low side.

A comparison of two- and six-inch modified ring tests was made for ten samples of liners in order to clarify this matter. Five samples of fourdrinier kraft liner were selected with basis weights in the range of 29 to 39-lb./1000 sq. ft. In addition, five samples of 42-lb. liner were also tested in both ring sizes to establish with certainty that six-inch rings are appropriate for that grade. Each test sample consisted of ten specimens which were tested on an H. and D. compression tester. The program was repeated on a later day. Except for the time difference between the two trials, all other test conditions were ostensibly the same between trials (same operator, same testing machine and the materials samples by the same sampling pattern).

The results of this study are shown in Table VI. In addition to listing the six-inch and two-inch ring strengths and their per cent difference, the results of tests of statistical significance are given. The latter were obtained by t-tests, and significance at the 5% level was examined.

TABLE VI

COMPARISON OF TWO-INCH AND SIX-INCH MODIFIED RING COMPRESSION STRENGTH (CROSS-DIRECTION)

Code No.	Basis Weight, lb./1000 sq.ft.	Caliper, pts.	Modified Ring Compression, lb./in. — Trial 1: Ring Size 6-in.	Trial 1: Ring Size 2-in.	Trial 1: Diff., %[a]	Trial 1: Significance[b]	Trial 2: Ring Size 6-in.	Trial 2: Ring Size 2-in.	Trial 2: Diff., %[a]	Trial 2: Significance	Composite—Trial 1 and 2: Ring Size 6-in.	Composite: Ring Size 2-in.	Composite: Diff., %[a]	Composite: Significance
4428	29.0	8.1	9.7	10.0	+3.1	No	10.0	10.4	+4.0	No	9.9	10.2	+3.0	Yes[c]
1191	33.1	8.9	12.6	13.4	+6.3	Yes	12.0	12.9	+7.5	No	12.3	13.1	+6.5	Yes
2168	34.3	10.0	12.6	12.1	-4.0	No	12.0	12.2	+1.7	No	12.3	12.2	-0.8	No
2350	38.4	11.1	16.5	17.6	+6.7	Yes	16.6	16.5	-0.6	No	16.5	17.1	+3.6	No
2222	38.9	11.4	15.0	14.0	-6.7	Yes[c]	14.5	14.9	+2.8	No	14.7	14.4	-2.0	No
				Av.	+1.1			Av.	+3.1			Av.	+2.1	
2006	42.2	12.9	16.4	16.2	-1.2	No	16.6	16.4	-1.2	No	16.5	16.3	-1.2	No
2078	42.4	12.7	18.6	17.5	-5.9	Yes	18.6	18.6	0.0	No	18.6	18.0	-3.2	No
2208	43.0	11.4	17.5	17.8	+1.7	No	17.4	17.4	0.0	No	17.5	17.6	+0.6	No
1169	43.1	12.6	17.0	16.4	-3.5	No	16.3	16.6	+1.8	No	16.7	16.5	-1.2	No
1185	43.2	12.7	16.1	16.8	+4.3	No	16.8	17.2	+2.4	No	16.5	17.0	+3.0	No
				Av.	-0.9			Av.	+0.6			Av.	-0.4	

[a] Diff., % based on 6-inch ring values.
[b] Significance obtained by the student "t" test at the 5% level.
[c] A borderline case of significance.

With regard to lightweight liners (below 42-lb.), there was a slight trend for two-inch ring strength to be higher than six-inch ring, but the trend is not very strong. Considering both trials, the two-inch value exceeded the six-inch value in seven out of ten instances, but only two of these instances were statistically significant. In one of the ten cases, there was a significant decrease in the two-inch ring value.

Compositing the two trials (as seems justified because there were no apparent systematic differences between trials), the two-inch ring strength was significantly higher than the six-inch value in the case of the two lightest weight liners (29.0 and 33.1 lb./1000 sq. ft.). No difference was observed with a 34-lb. liner sample or with two 38-lb. liners.

It would appear on the basis of these data, therefore, that two-inch modified ring specimens may be beneficial for the testing of liners in weights of 33-lb. and below. However, the improvement over the six-inch ring strength can be expected to be modest—about 3%, on the average.

In the case of 42-lb. liners there was only one significant difference between two- and six-inch modified ring strength in ten comparisons. In the composite of the two trials there were no significant differences. It is not recommended, however, that a two-inch ring be used on this or heavier grades because forming the specimen to the high curvature of the two-inch ring possibly may damage the specimen.

Returning to consideration of Fig. 1 and the two lightweight samples which fell off from the straight line, the less severe of these cases (Sample 2168) was also tested as a two-inch ring in the present considerations. As shown in Table VI, no increase in load was experienced with the two-inch modified ring. There is no strong reason, therefore, to believe that the two points corresponding to the lightweight samples should not be displaced from the straight line.

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APPENDIX

MECHANICAL ANALYSIS OF THE H. AND D. AND RIEHLE COMPRESSION TESTERS

Both the H. and D. and the Riehle testing machines can be represented by the spring system shown in Fig. 6, where K refers to the spring constant (load-to-deflection ratio) of the beam in the weighing system and S is the spring constant (or stiffness, lb./in.) of the specimen undergoing test.

When the platens of the H. and D. tester (500-lb. beam) are driven in direct contact (no specimen present) the rate of loading is approximately 900 lb./min. and the rate of platen motion is 0.9 in./min. Thus, the spring constant of the beam is

$$K_H = \frac{900}{0.9} = 1000 \text{ lb./in.}$$

Calibration of the modified Riehle tester in this laboratory revealed that the loading rate (platen-to-platen) is about 1950 lb./min. and the platen rate is 0.1932 in./min. Thus, the spring constant is approximately

$$K_R = \frac{1950}{0.1932} \doteq 10,000 \text{ lb./in.},$$

that is, ten times higher than the H. and D. spring constant.

Consider the mechanical system of Fig. 6 when the upper platen has traveled a distance x_u, reckoned from the inception of load on the specimen. A portion of this motion will be accommodated by deformation e in the specimen and the remainder will be a displacement x_b of the lower platen (and, hence, a deformation of the machine spring in the amount x_b). The deformation of the specimen is

$$e = x_u - x_b \qquad (1)$$

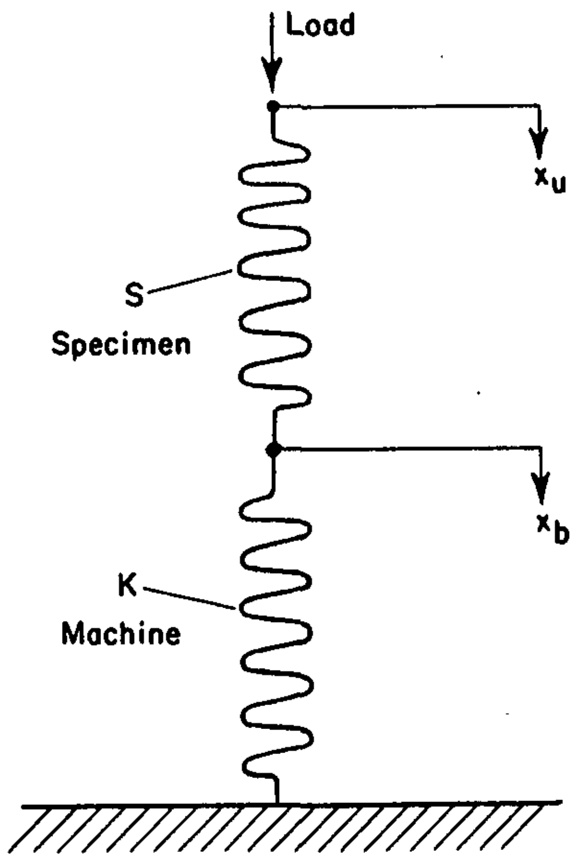

Figure 6. Representation of Testing Machine and Specimen as Two Springs in Series

The total load in the specimen and the load in the machine spring are equal. From the definition of spring constant, therefore, it follows that

$$Se = K\,x_b \tag{2}$$

Substituting for x_b from Equation (1),

$$e = \left(\frac{K}{S + K}\right)x_u \tag{3}$$

Differentiating Equation (3) with respect to time, the deformation rate, de/dt, in the specimen is given by

$$\frac{de}{dt} = \left(\frac{K}{S + K}\right)\frac{dx_u}{dt} \tag{4}$$

provided the specimen load is within the proportional limit (*i.e.*, $dS/dt = 0$). dx_u/dt is the rate of motion of the upper platen.

It may be noted that if the specimen is very "soft" relative to the weighing beam ($S \ll K$), the specimen deformation rate approaches the platen rate (and there is little deformation of the machine spring). On the other hand, for a relatively stiff specimen ($S \gg K$), its deformation rate is low (and most of the platen motion is taken up by deflection of the machine spring).

Figure 3 in the main body of the report is a graph of Equation (4) for the H. and D. and Riehle testers described above. It may be seen that for a specimen stiffness less than about 7000 lb./in. the deformation rate in the specimen is greater in the H. and D. tester, while for greater values of specimen stiffness, the Riehle deformation rate exceeds the H. and D. rate by a modest amount.

The stiffness S of the test specimen may be expressed as

$$S = Etb/L \tag{5}$$

where E = modulus of elasticity

t = caliper

b = width

L = span

For the regular ring test, b = 6 in., L = 0.5 in., and Reference (4) gives several values of Et ranging from about 1100 to 1600 lb./in. for 42-lb. liners and 1600 to 2200 lb./in. for 69-lb. liners. The corresponding range of S is about 13,000 to 18,000 for 42-lb. liners and 18,000 to 24,000 for 69-lb. liners. Reference to Fig. 3 shows that the Riehle deformation rate exceeds the H. and D. rate by about 25 to 50% in this range.

Beyond the proportional limit of the specimen load-deformation curve, account must be taken that the specimen stiffness decreases with e and hence with time, t. In this range, the specimen stiffness (which may be denoted as S_i) is the "chord modulus," as illustrated in Fig. 7. Equation (3) still applies, provided S is replaced by S_i, that is,

$$e = \left(\frac{K}{S_i + K}\right)x_u \tag{3'}$$

Differentiating Equation (3') with respect to time gives

$$\frac{de}{dt} = \frac{K}{S_i + K}\frac{dx_u}{dt} - x_u\frac{K}{(S_i + K)}\frac{dS_i}{dt} \tag{6}$$

But,

$$\frac{dS_i}{dt} = \frac{dS_i}{de}\frac{de}{dt} \tag{7}$$

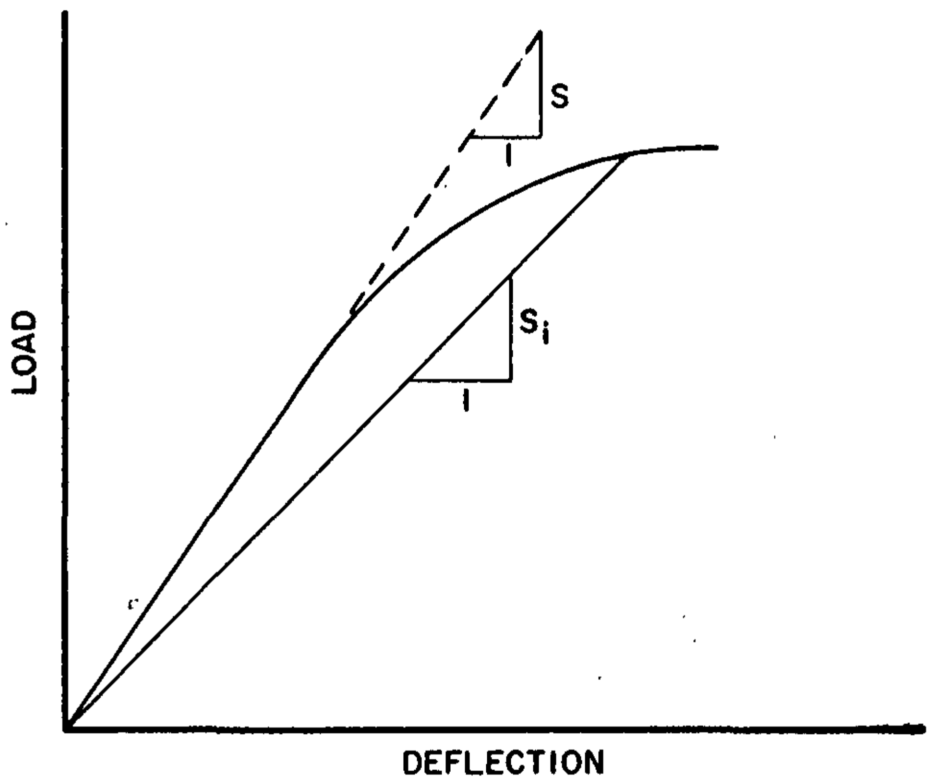

Figure 7. Stiffness, S_i, of Specimen in the Inelastic Range

Thus, dS_i/dt may be eliminated from Equation (6) by means of Equation (7), and x_u may be eliminated from Equation (6) by means of Equation (3'). Making these substitutions and solving for de/dt gives

$$\frac{de}{dt} = \left(\frac{K}{S_i + e\frac{dS_i}{de} + K} \right) \frac{dx_u}{dt} \qquad (8)$$

Equation (8) is seen to be similar to its elastic equivalent, namely, Equation (4); the only difference is that S is replaced by a function of the inelastic stiffness S_i. Equation (8) may be regarded as the generalized form of a deformation rate equation for this type of testing machine. In the elastic range of the specimen, $S_i = S$, $dS_i/de = 0$ and Equation (8) reduces to Equation (4).

Moreover, since in the inelastic range $S_i < S$ and dS_i/de is always negative for conventional paperboards, the term $(S_i + e\ dS_i/de)$ is always less than the elastic S. In terms of Fig. 3, the abscissa may be entered at $(S_i + e\ dS_i/de)$ and this point will always lie to the left of the elastic S on the graph. In other words, in the inelastic range the specimen behaves like a specimen of lower stiffness and this leads to higher deformation rates in both the H. and D. and the Riehle testers.

In order to use Equation (8), it is necessary to know how S_i varies with e so that dS_i/de can be computed. While this may be accomplished graphically or numerically from a load-deformation curve of a material, it should suffice for present purposes to consider the matter in a more general framework.

Suppose, for example, that the load-deformation curve can be approximated by a simple power function beyond the proportional limit, or in some more limited range of interest:

$$P = ae^n \qquad (9)$$

where n is typically a fraction, P is load, and a is a constant. The fit of this curve below the proportional limit is of no consequence to the present discussion. The value of S_i at any point in the range of the approximation is

$$S_i = \frac{P}{e} = \frac{ae^n}{e} = ae^{n-1}$$

then,

$$\frac{dS_i}{de} = (n - 1)ae^{n-2}$$

and

$$S_i + e\frac{dS_i}{de} = ae^{n-1} + (n - 1)ae^{n-1}$$

$$= nae^{n-1}$$

$$= nS_i \qquad (10)$$

For a rough estimate, inspection of several ring compression curves indicates that S_i near failure is about 0.8 of the elastic S. In this same region, n of Equation (9) appears to be about 0.4, whereupon the function given by Equation (10) is about 1/3 of the elastic stiffness, that is, as low as 4000 lb./in. in the case of 42-lb. liner. Reading into Fig. 3 at this value of stiffness it is found that the H. and D. deformation rate is 0.18 in./min. and the Riehle rate is 0.14 in./min. That is, near failure of the ring specimen of this example the deformation rate in the H. and D. exceeds the Riehle rate by about 30%.

The development given above for strain rate has generality in that it applies to any machine (tension or compression) that employs a spring in the weighing system (specifically a spring with linear load-deflection characteristics). Specimen strain rates may be estimated for tests other than ring compression (e.g., flat crush or Concora medium test) provided the load-deformation characteristics of the specimen are known. These characteristics can be obtained with probably sufficient accuracy from a testing machine giving a load-deformation recording at a test rate of the same order of magnitude as in the machine under study.