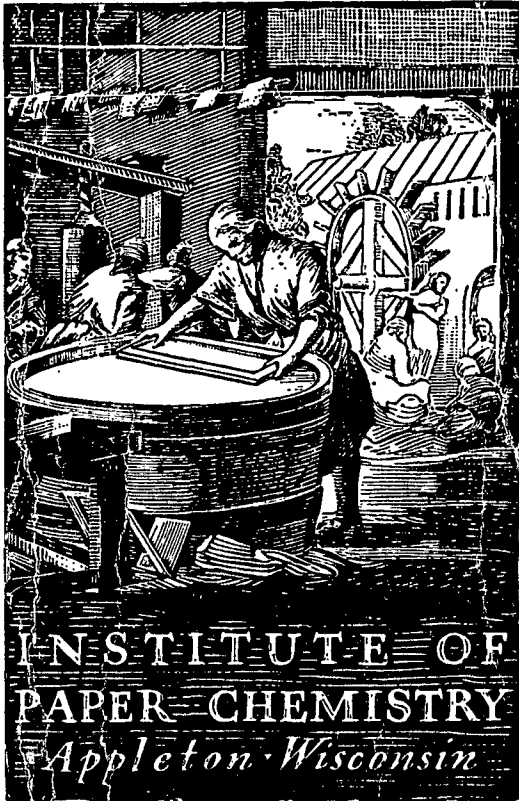


GENERAL



**RELATIONSHIPS BETWEEN ELASTIC PROPERTIES
AND END-USE PERFORMANCE**

Project 2695-23

**Report One
to
FOURDRINIER KRAFT BOARD GROUP
OF THE
AMERICAN PAPER INSTITUTE**

January 30, 1985

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

RELATIONSHIPS BETWEEN ELASTIC PROPERTIES AND END-USE PERFORMANCE

Project 2695-23

by

William J. Whitsitt

Report One

to

FOURDRINIER KRAFT BOARD GROUP

OF THE

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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

RELATIONSHIPS BETWEEN ELASTIC PROPERTIES AND END-USE PERFORMANCE

SUMMARY

The objective of this study was (1) to develop baseline test data on the ultrasonically determined elastic properties of linerboard and medium and (2) to relate the elastic properties to the strength properties of the components and combined board made therefrom. For this purpose we tested about 100 liner and medium samples from FKBG member mills. Many of these were also made into combined board and tested for ECT and flat crush.

Our results show

1. ECT is well related to STFI tests on the components as well as to ring crush. It is equally well related to the elastic stiffnesses. This supports use of the ultrasonically determined elastic properties in testing and on-machine control.
2. The following equation relates ECT and the CD STFI compressive strengths of the components: $ECT = 0.685(2S_l + DS_m) + 4.62$ where S_l and S_m are CD STFI compressive strengths of the liners and medium, respectively. D is the draw or take-up factor.
3. STFI and ring crush results are highly correlated with the elastic stiffnesses but in somewhat different ways. Because of the ring geometry, the ring crush results indicate that the stiffnesses in the MD, CD and ZD directions must be considered

along with density. STFI results depend on the elastic stiffness in the direction of load and the out-of-plane stiffness.

4. Bursting strength is fairly well related to the in-plane shear stiffness or geometric mean stiffness as expected from theory. However the burst correlations with elastic stiffnesses were lower than the relations between compressive strength and stiffnesses.
5. The combined board flat crush strengths of the heavier weight mediums were often low per unit weight of medium fiber. Corrugating pressure patterns show that most of the corrugating roll pressure is imposed on the sidewalls in the case of thick, high weight medium rather than on the tips in the case of 9-pt. medium. As a result, the fluted flanks suffer more caliper loss and fiber-to-fiber bonding damage. This lowers the ultimate flat crush strength of the flute. This suggests that changes in flute contour or increased densification (e.g., by wet pressing) are two approaches to minimize the strength losses.

INTRODUCTION

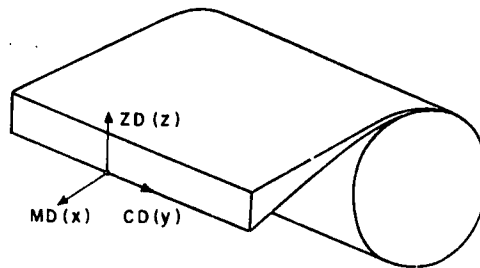
The objective of this program was to develop baseline test data on the ultrasonically determined elastic properties of linerboard and medium and to relate the elastic property results to the strength properties of the components and combined board. We evaluated the elastic, compressive strength and other properties of about 50 linerboard and 50 medium sample lots from FKBG member mills. The properties tested included six elastic stiffnesses, ring crush, STFI and Taber stiffness on all sample lots. In addition, at the request of the Technical Committee, we made Mullen tests on the linerboard and Concora tests on the medium.

In order to determine relationships between the elastic stiffnesses of the components and combined board quality we fabricated single-faced boards from the various sample lots. For this purpose sheets of the mediums were combined with a "standard" 42-lb liner on the Institute's pilot corrugator. In a similar way the various linerboards were combined with a standard 26-lb medium. The medium fabrication was carried out at speeds of 200, 400, and 600 fpm; the liner fabrication at 400 fpm. The boards were inspected for fabrication quality, and the 400 fpm samples were selected for tests. The single-faced boards were tested to determine their flat crush load-deformation curve characteristics. ECT tests were carried out on manually double-backed samples.

In our analyses we have developed relationships between the strength tests and the elastic stiffnesses. These results are summarized herein.

BACKGROUND - ELASTIC STIFFNESSES

Paperboard is characterized by nine independent elastic constants. There are three Young's moduli, three shear moduli, and three Poisson ratios (see Fig. 1).



ELASTIC PROPERTIES

- Young's Moduli: E_x, E_y, E_z
- Shear Moduli: G_{xy}, G_{xz}, G_{yz}
- Poisson Ratios: $\mu_{xy}, \mu_{xz}, \mu_{yz}, \dots$

IN-PLANE MODULI

- E_x, E_y, G_{xy}

OUT-OF-PLANE MODULI

- G_{xz}, G_{yz}, E_z

Figure 1. Orthotropic axes and elastic properties.

In the ultrasonic tests a velocity (V) of the appropriate wave type and direction is measured. In general, the specific stiffnesses are proportional to V^2 . The specific stiffness is equal to a modulus (E) per unit density (ρ) or may be regarded as stiffness (Et) per unit of basis weight. The specific stiffnesses can be transformed to stiffnesses (Et or Gt) or moduli (E or G) by multiplying V^2 by either basis weight or density, respectively.

The appropriate form must be selected when relating the elastic constants to strength properties. For example, compressive strength in force/width should be related to the stiffnesses (Et) and compressive strength per unit

weight (index) to the specific stiffnesses (E/ρ). This is essential for physical and dimensional consistency.

Empirical relationships between the shear and Young's moduli are often useful in working with the elastic properties. Such relationships are analogous to the known relationship between E and G for isotropic materials. For paper and paperboard these take the forms (1):

$$G_{xyt} = k_1 [(E_{xt})(E_{yt})]^{1/2} \quad (1)$$

$$G_{xz t} = k_2 [(E_{xt})(E_{zt})]^{1/2} \quad (2)$$

$$G_{yz t} = k_3 [(E_{yt})(E_{zt})]^{1/2} \quad (3)$$

where $k_1, k_2, k_3 = \text{constants}$

Figures 2-4 show that these relationships hold quite well for linerboard over the range of grade weights. Similar results were obtained for medium, although there is more scatter in the out-of-plane relations for $G_{xz t}$ and $G_{yz t}$.

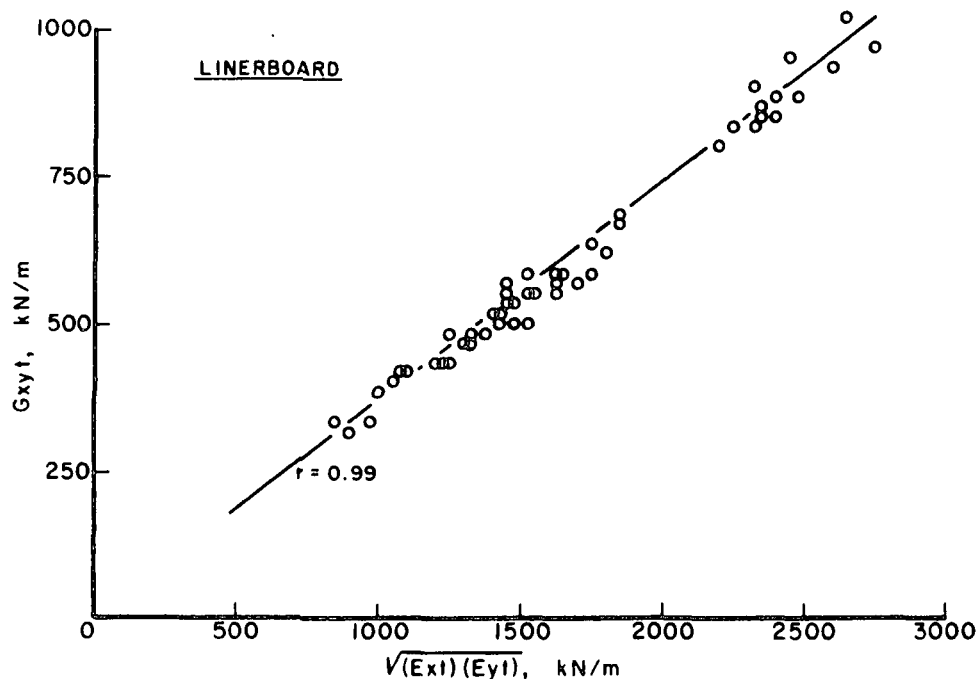


Figure 2. G_{xyt} is well related to the geometric mean in-plane stiffnesses.

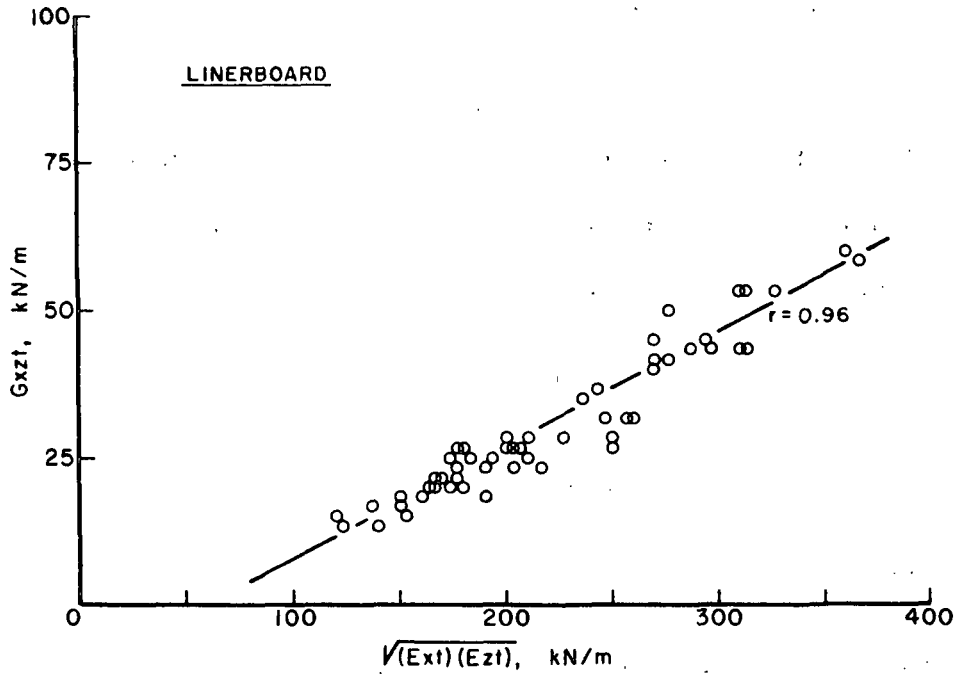


Figure 3. MD out-of-plane shear vs. Young's stiffnesses.

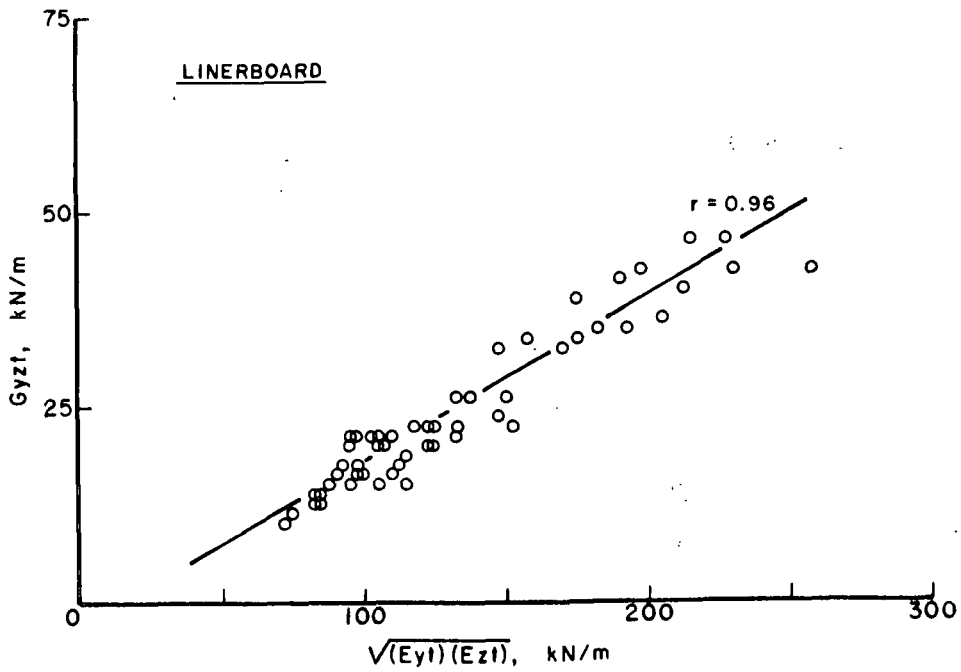


Figure 4. CD out-of-plane vs. Young's stiffnesses.

In the on-machine measurements of the in-plane properties we make use of an empirical relationship between G_{xyt} and the geometric mean $[(E_{xt})(E_{yt})]^{1/2}$. For the results in Fig. 2 a strong relationship between the in-plane properties is evident. Thus, these results help justify the use of this relationship in on-machine applications. The following equation is obtained

$$G_{xyt} = - 0.38 + 0.367 \sqrt{(E_{xt})(E_{yt})}$$

By making use of such relations we can relate compressive strength to two stiffnesses rather than three as is discussed in Ref. (2).

RESULTS

BASELINE RESULTS - STRENGTH TESTS

Table 1 summarizes the linerboard and medium results by grade weight. In this table the results are expressed in the customary trade units for the particular test. For other purposes we have also summarized the results in TAPPI - ISO units, converting the compressive strength results to strength per unit weight - ISO Index (See Table 2). Detailed tables showing the results for each sample lot are appended.

Figure 5 shows that the average linerboard CD ring crush results ranged from 43.6 for 26-lb liner to 129.7 for 69-lb liner. In each grade weight there were wide variations in strength between sample lots, with coefficients of variation ranging from about 10 to 12%. The maximum and minimum values shown in Fig. 5 reflect this variation, e.g., for 42-lb liners the CD ring crush values ranged from about 68 to 100 lb, a range of about 40%. Such variations in liner strength will cause appreciable differences in combined board ECT strength.

For medium, Fig. 5 shows that the average CD ring crush values increased from 39.1 on 26-lb mediums to 57.0 for 40 to 42-lb mediums. Wide variations in ring crush occurred between lots as shown by the maximum and minimum values for each grade. The coefficients of variation for medium were about the same or smaller than on comparable linerboard grade weights.

The CD ring crush indexes (strength/unit weight in ISO units)* for 33- to 69-lb linerboards are about 11+ Nm/g (Table 2), but the index for the 26-lb liners was about 13+% lower. The lower strength index for the 26-lb linerboard

*lb/inch x 175.13 = N/m.

N/m divided by basis weight in g/m^2 = Index in Nm/g.

Table 1. Summary of strength results on linerboard (customary units).

Nom. Grade Weight, lb/1000 ft ²	No. of Lots	Basis Weight, lb/1000 ft ²	Caliper, mil TAPPI	Density, lb/ream-mil TAPPI	STFI lb/inch		Ring Crush, lb/6 inches		Taber Stiffness, g-cm	
					MD	CD	MD	CD	MD	CD
LINERBOARD										
26	5	Av. 27.1 Max 28.9 Min 26.3 CV 3.9	8.17 7.19 7.79 4.7	3.322 3.714 3.076 7.3	23.95 28.50 18.78 14.6	12.28 13.37 10.81 8.4	64.3 68.7 58.4 6.2	43.6 51.0 37.5 12.2	16.0 18.8 14.0 12.6	7.6 8.5 6.9 9.0
33	15	Av. 33.8 Max 35.1 Min 32.8 CV 2.2	10.37 11.57 9.19 5.7	3.273 3.723 3.339 6.0	28.60 35.34 23.09 11.3	15.77 19.68 13.76 11.0	90.2 113.3 71.1 12.3	63.8 79.7 54.0 11.4	35.5 59.8 23.0 24.3	16.7 23.3 11.0 17.9
42	20	Av. 42.4 Max 44.6 Min 40.1 CV 2.4	12.41 13.67 11.16 6.3	3.432 3.810 3.394 6.9	35.69 40.88 31.38 7.6	19.33 24.81 16.70 10.7	115.7 137.0 88.8 10.3	81.1 100.0 67.7 11.1	67.1 108.5 41.0 20.5	29.4 38.0 19.4 16.4
69	16	Av. 69.4 Max 73.0 Min 67.8 CV 2.2	20.51 22.64 17.63 6.9	3.396 3.923 3.405 5.9	51.71 60.33 46.47 7.7	30.80 37.44 23.47 10.7	177.1 207.3 158.5 8.1	129.7 152.1 108.3 9.7	272.8 369.0 194.5 18.8	115.6 146.0 80.5 16.0
MEDIUM										
26	26	Av. 26.4 Max 27.0 Min 25.0 CV 1.7	10.58 12.15 8.98 9.3	2.513 2.995 2.167 9.5	20.66 23.21 18.34 6.9	12.19 14.61 9.43 9.4	56.5 66.6 41.8 10.3	39.1 45.9 29.1 10.9	15.7 23.7 10.7 17.5	7.6 13.3 4.6 26.6
33-36	13	Av. 33.8 Max 37.0 Min 33.0 CV 3.7	12.91 14.84 10.65 9.4	2.641 3.104 2.227 8.3	26.66 30.33 23.21 7.6	16.81 19.80 13.85 9.3	86.4 98.4 72.4 8.2	62.5 69.6 53.1 8.8	31.9 43.4 22.1 20.0	15.3 21.6 11.0 23.0
40-42	9	Av. 40.8 Max 43.7 Min 39.4 CV 3.7	15.65 17.09 13.40 7.5	2.620 2.949 3.025 7.3	31.58 35.55 27.72 8.3	19.78 22.06 18.28 6.6	114.8 129.3 101.1 7.8	81.5 90.2 69.4 8.5	57.0 71.0 44.6 13.9	28.4 34.4 22.0 14.5
52	1	Av. 54.2	18.91	2.866	41.22	27.47	150	108.1	162.5	56.2

Note: CV = coefficient of variation (percent standard deviation).

Table 2. Summary of strength results per unit weight.

Nom. Grade Weight, lb/1000 ft ²	No. of Lots	Basis Weight, g/m ²	Caliper, μ m		Density, kg/m ³		STFI Index, Nm/g		Ring Crush Index, Nm/g				
			TAPPI	IPC	TAPPI	IPC	MD	CD	MD	CD			
LINERBOARD													
26	5	Av. CV	132.2 3.9	208 4.7	171.8 5.3	639 7.3	772 8.4	31.7 12.3	16.3 7.7	1.94 --	14.2 7.8	9.6 12.3	1.47 --
33	15	Av. CV	165.1 2.2	264 6.4	224 5.7	629 6.9	739 6.0	30.3 10.4	16.7 10.8	1.81 --	15.9 11.6	11.3 11.2	1.41 --
42	20	Av. CV	207.2 2.4	315 6.3	277 6.5	660 6.5	752 6.9	30.2 7.5	16.3 9.5	1.85 --	16.3 9.1	11.4 9.8	1.43 --
69	16	Av. CV	339 2.2	521 6.9	472 6.4	653 6.6	720 5.9	26.7 7.2	15.9 10.9	1.67 --	15.3 7.9	11.2 10.1	1.37 --
MEDIUM													
26	26	Av. CV	128.7 1.7	269 9.3	189 5.8	483 9.5	682 5.8	28.1 6.1	16.6 9.3	1.69 --	12.8 9.6	8.9 10.9	1.45 --
33-36	13	Av. CV	165.2 3.7	328 9.4	246 8.2	508 9.3	677 8.3	28.3 7.1	17.8 8.1	1.59 --	15.3 7.2	11.0 7.5	1.38
40-42	9	Av. CV	199.2 3.7	398 7.5	307 7.0	504 8.5	652 7.3	27.8 7.4	17.4 8.4	1.60	16.8 6.9	11.9 7.9	1.41
52	1	Av.	265	480	387	551	684	27.3	18.2	1.50	17.6	11.9	1.47

Note: CV = Coefficient of variation (percent standard deviation).
Index = Strength/unit weight in ISO units.

is a result of the buckling mode of failure characteristic of ring crush tests on lightweight linerboards. The corrugating medium ring crush results show a similar trend. Inspection of the CD STFI index results in Table 2 shows that essentially the same indexes (strength per unit weight) are achieved over this basis weight range in the case of both linerboard and medium. Thus the STFI test is a better measure of compressive strength on light weight sheets than ring crush.

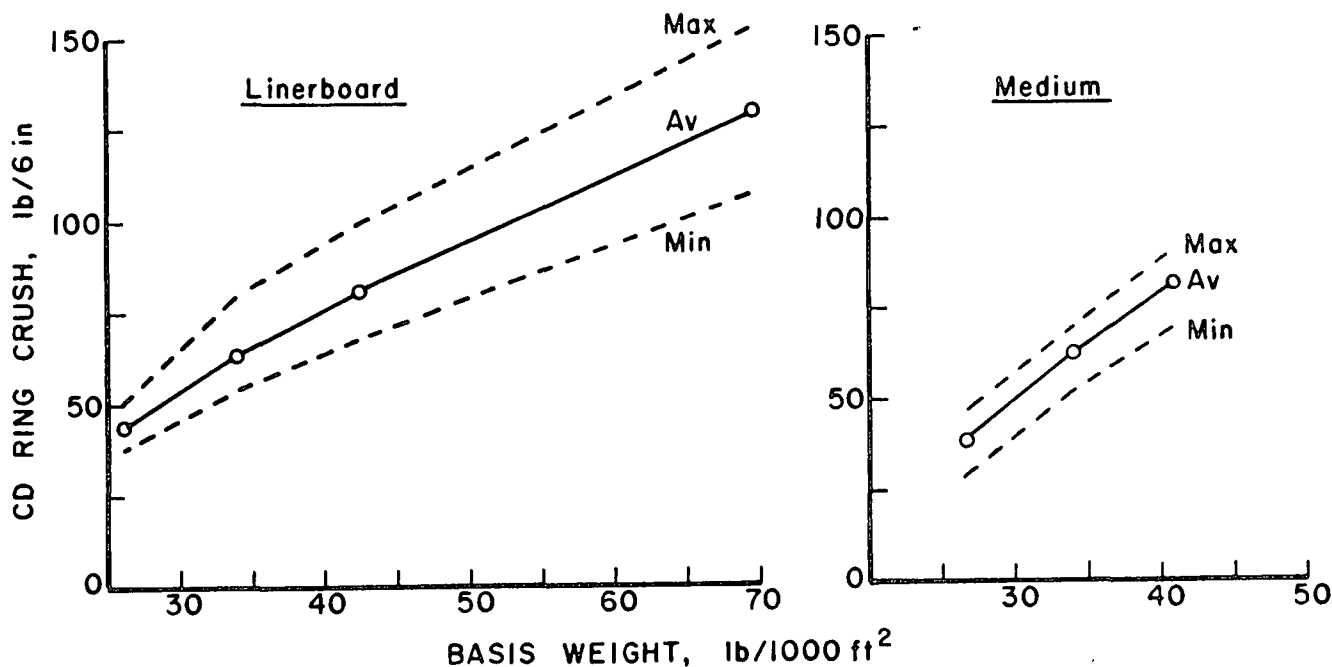


Figure 5. Average CD ring crush results.

Figure 6 shows that the average CD STFI medium and linerboard results increase linearly with increasing basis weight (to be expected because strength/unit weight was about constant). The STFI variations between sample lots were generally somewhat lower than obtained with the ring crush tests, particularly on the lighter weight grades.

The MD/CD STFI ratios are greater than obtained with ring crush on both linerboard and medium (Fig. 7). This indicates the tests are affected differently by such papermaking factors as fiber orientation and wet strain. Thus,

the mechanisms of failure must differ to some extent. We speculate such differences could arise due to the circular configuration and buckling modes of failure in the ring crush test. As one consequence of the directional differences the relationships between STFI and ring crush will differ for the MD and CD directions as discussed in later pages.

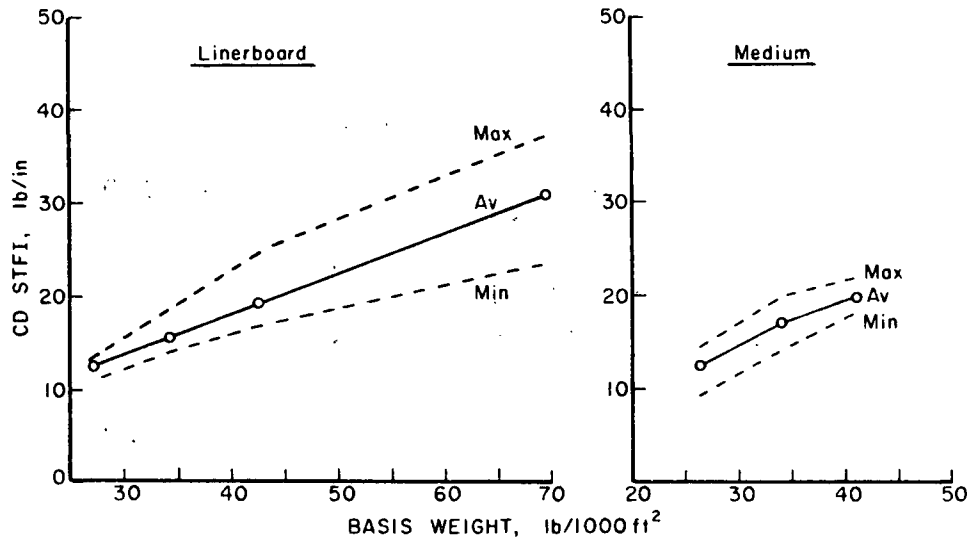


Figure 6. Average CD STFI results.

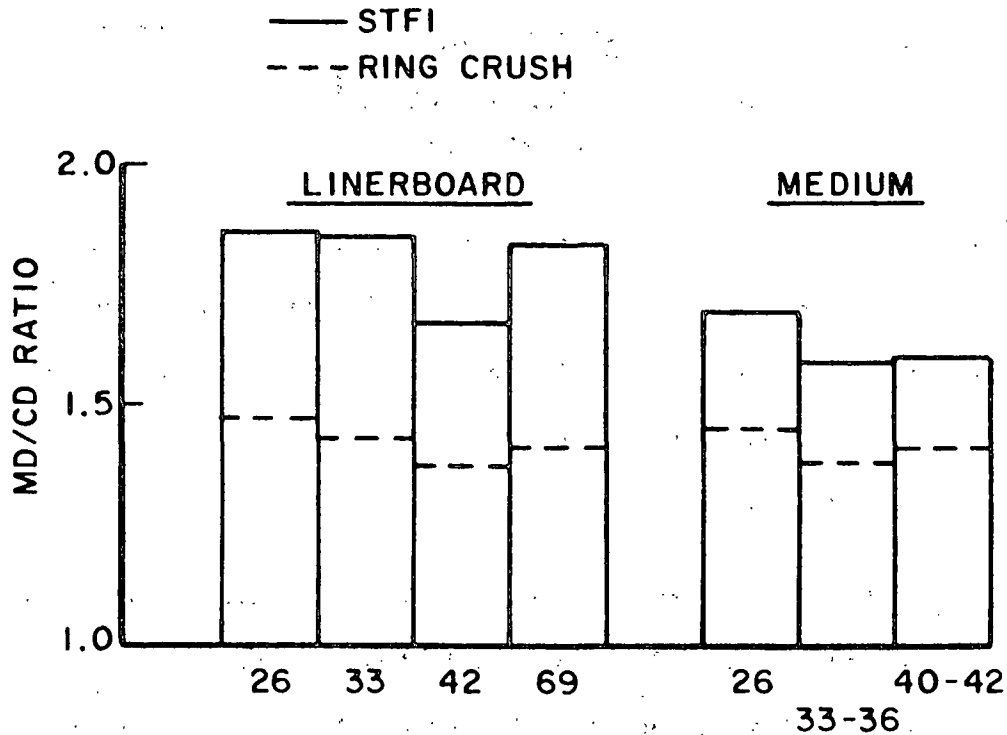


Figure 7. MD/CD compressive strength ratios.

BASELINE RESULTS - ELASTIC STIFFNESSES

Table 3 summarizes the elastic stiffness results by grade weight. The specific stiffnesses, i.e., stiffness per unit weight, are shown in Table 4. Detailed results for each sample lot are appended.

Table 3. Summary of elastic stiffness results.

Nom. Grade Weight, lb/1000 ft ²	No. of Lots		Stiffness ^a , kN/m				G _{xzt}	G _{yzt}	R ^b
			E _{xt}	E _{yt}	G _{xyt}	E _{zt}			
LINERBOARD									
26	5	Av.	1674	551	363	13.2	15.9	13.2	3.16
		CV	9.6	20.4	10.3	35.0	10.8	13.0	25.1
33	15	Av.	2142	772	468	14.4	22.1	18.5	2.85
		CV	12.8	15.7	7.2	25.1	20.1	20.4	18.9
42	20	Av.	2750	934	575	16.3	27.6	22.7	3.00
		CV	9.4	16.3	6.7	34.2	16.4	20.1	21.1
69	16	Av.	3822	512	882	23.4	47.3	38.9	2.69
		CV	10.4	18.2	8.6	21.7	15.3	14.7	38.2
MEDIUM									
26	26	Av.	1306	506	298	19.6	16.8	14.5	2.64
		CV	14.4	14.5	8.5	12.2	11.7	9.6	22.7
33-36	13	Av.	1616	695	390	29.2	26.4	23.8	2.35
		CV	15.2	10.5	9.0	18.3	10.6	18.2	18.2
40-42	9	Av.	1961	854	469	32.6	35.5	30.6	2.32
		CV	18.6	14.4	11.5	13.3	8.6	9.8	19.2
52	1	Av.	2983	1284	707	42.8	62.6	50.6	2.32

^aStiffness = appropriate acoustic velocity squared x basis weight in g/m².

^bR = E_{xt}/E_{yt}.

Note: CV = coefficient of variation (percent standard deviation).

Table 4. Summary of stiffness results per unit weight. (Modulus Per Unit Density ρ .)

Nom. Grade Weight, lb/1000 ft ²	No. of Lots		Specific Stiffness, MNm/kg				
			E_x/ρ	E_y/ρ	G_{xy}/ρ	E_z/ρ	R^a
LINERBOARD							
26	5	Av.	12.65	4.17	2.74	0.099	3.16
		CV	8.1	21.1	9.5	31.4	25.1
33	15	Av.	12.25	4.45	2.70	0.087	2.85
		CV	13.6	22.5	15.2	24.1	18.8
42	20	Av.	13.12	4.50	2.77	0.078	3.00
		CV	10.0	14.9	5.0	34.7	21.1
69	16	Av.	11.26	4.47	2.61	0.069	2.69
		CV	9.9	18.6	9.3	21.3	38.2
MEDIUM							
26	26	Av.	10.0	3.87	2.28	0.152	2.64
		CV	16.2	16.4	11.4	12.6	22.7
33-36	13	Av.	9.45	4.10	2.29	0.176	2.35
		CV	15.1	15.5	12.6	16.7	18.1
40-42	9	Av.	9.81	4.28	2.35	0.164	2.32
		CV	16.1	13.0	8.8	14.6	19.2
52	1	Av.	11.26	4.85	2.67	0.162	2.32

$$^aR = (E_x/\rho)/(E_y/\rho).$$

Note: CV = coefficient of variation (percent standard deviation).

Figures 8 and 9 show that the elastic stiffnesses increase with grade weight of linerboard and medium in the expected way. In general, for comparable basis weights corrugating medium has lower in-plane elastic stiffnesses but a higher out-of-plane Young's stiffness ($E_z t$). In Fig. 10 the cross direction in-plane specific stiffness of medium is nearly equal to that of linerboard, but medium exhibits much higher out-of-plane specific stiffnesses. The latter should be helpful in the fluting process because it favors compressive strength retention.

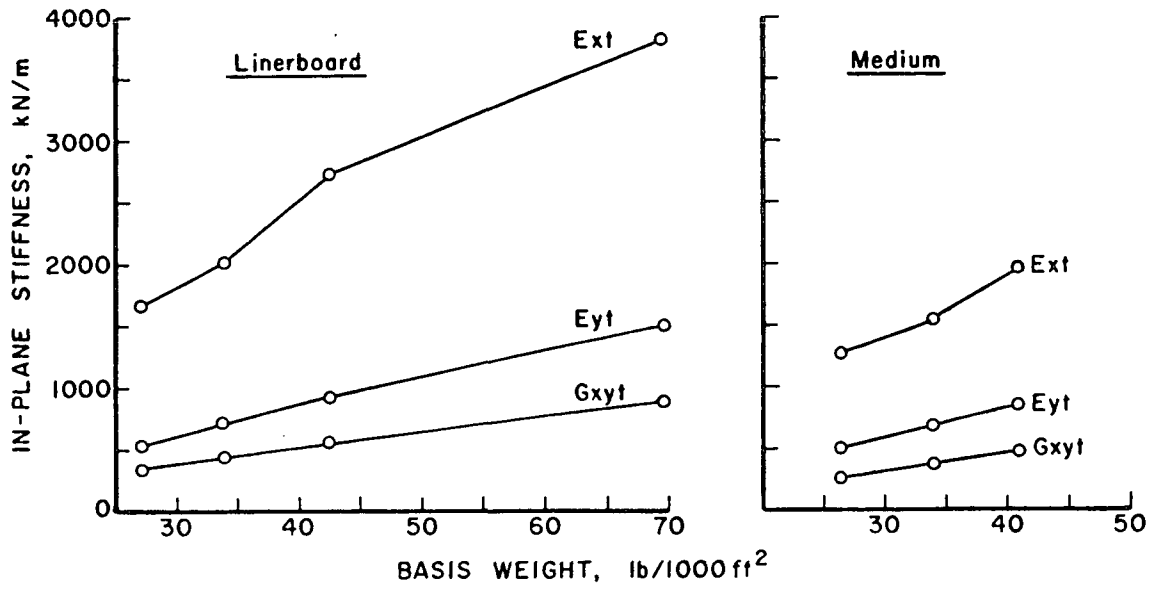


Figure 8. Average in-plane elastic stiffnesses for various grade weights of linerboard and medium.

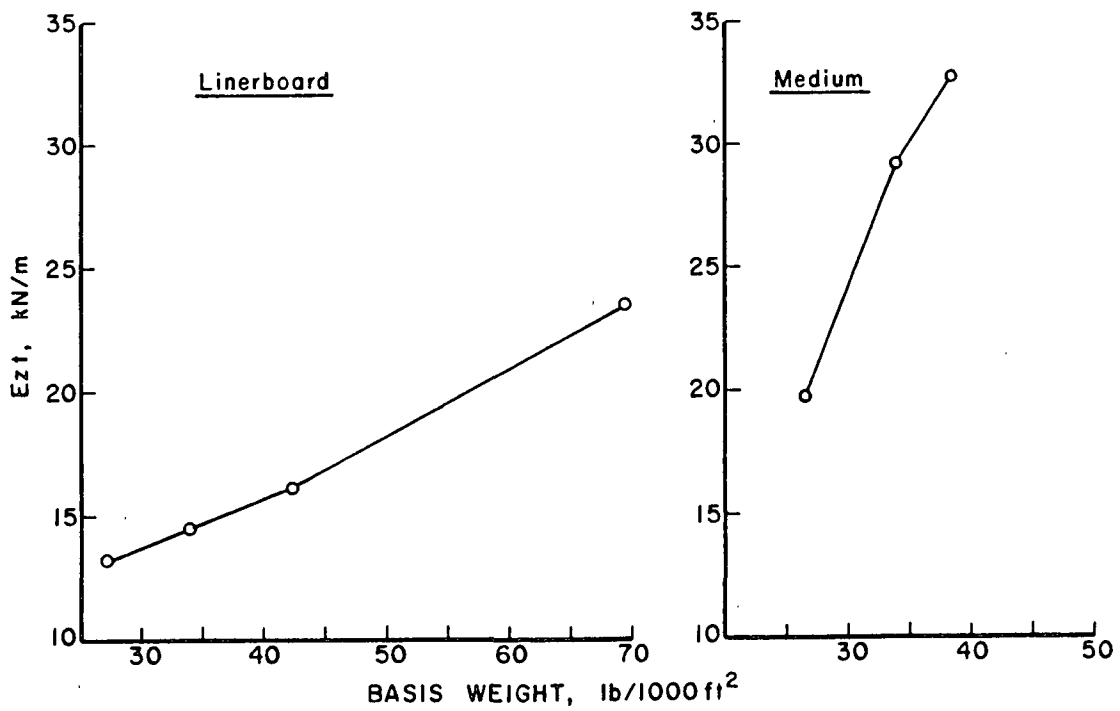


Figure 9. Average out-of-plane stiffnesses for various grade weights of linerboard and medium

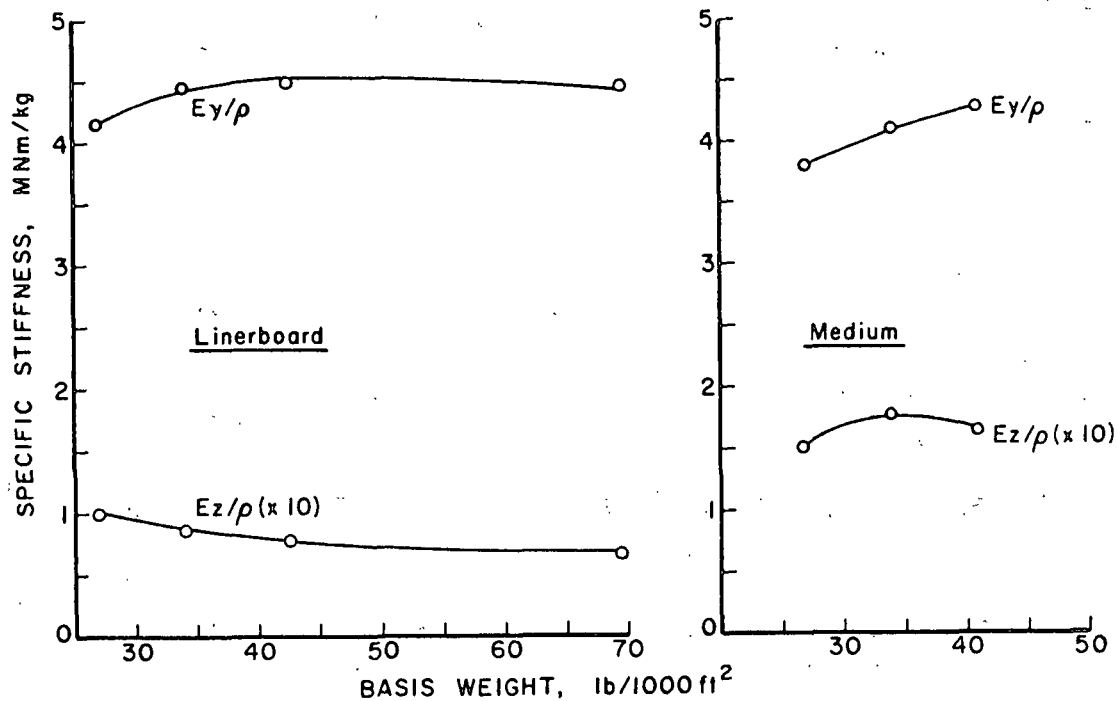


Figure 10. Average specific stiffnesses for various grade weights of linerboard and medium.

STFI COMPRESSION/RING CRUSH RELATIONSHIP

Cross direction relationships between STFI and ring crush are shown in Fig. 11-13. Relations are shown for lighter weight liners (Fig. 11), heavier weight liners (Fig. 12), and medium (Fig. 13). Good relationships were obtained for these grade weight ranges. Within separate grade weights the correlations were lower but reasonable as shown in Table 5.

Ring crush is a more complex test than STFI due to its cylindrical geometry. There are also differences in mode of failure. As discussed in later pages the two tests are related to the elastic stiffnesses and other parameters in somewhat different ways. This indicates the above relationships will not

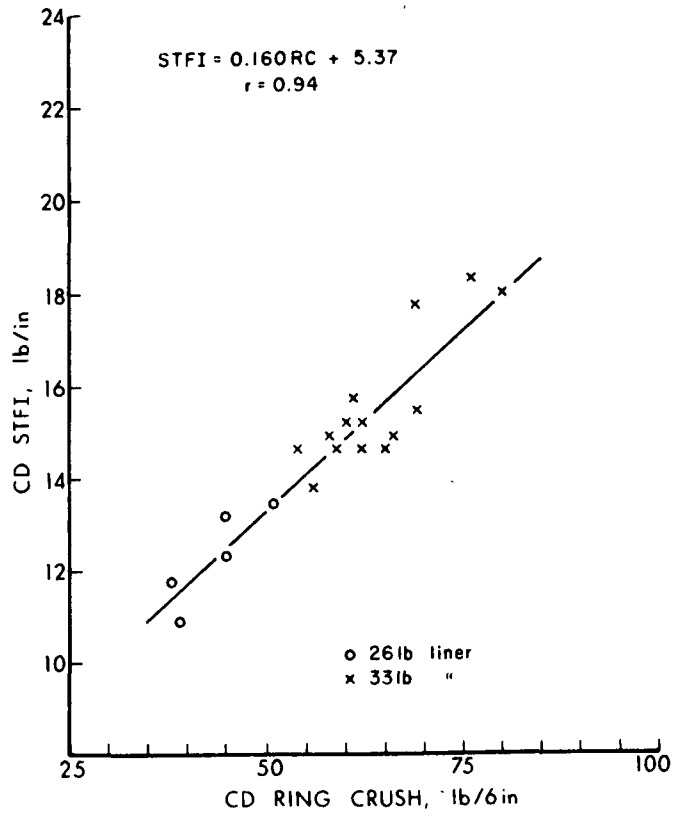


Figure 11. CD STFI vs. CD ring crush for lighter weight liners.

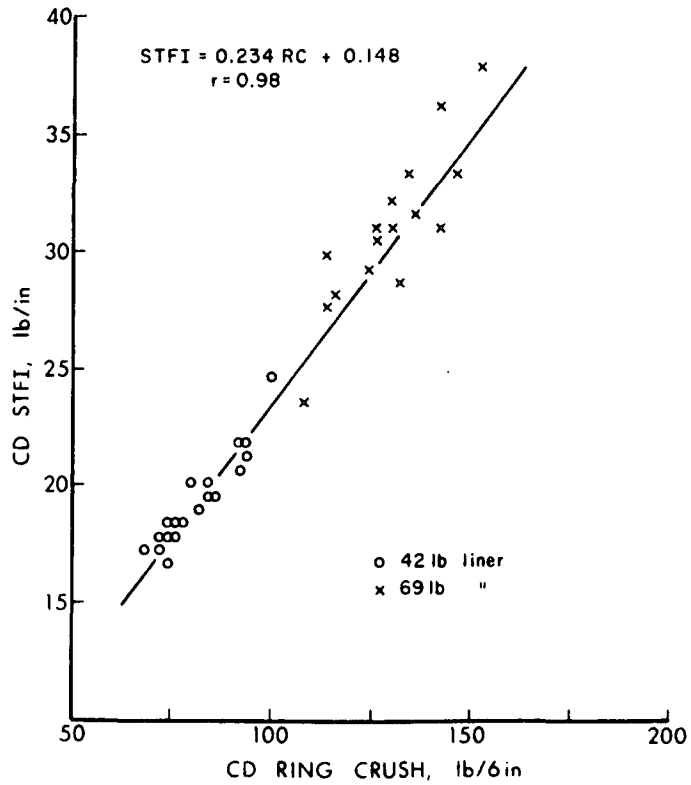


Figure 12. CD STFI vs. CD ring crush for heavier weight liners.

hold under all papermaking conditions. For example, densification by wet pressing is known to affect the two tests differently as discussed below.

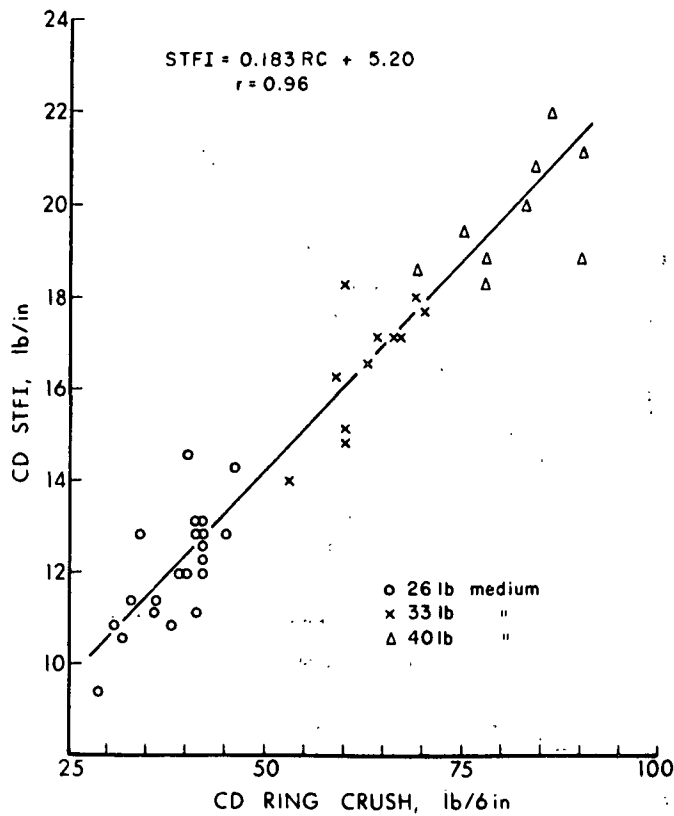


Figure 13. CD STFI vs. CD ring crush for corrugating medium.

Table 5. Within grade STFI vs. ring crush correlations.^a

Grade Weight	Slope, a	Intercept, b	Corr. Coeff.
26-1b liners	0.162	5.22	0.84
33-1b liners	0.158	5.37	0.85
42-1b liners	0.206	2.45	0.94
69-1b liners	0.226	1.43	0.86

^aCD STFI = a ring crush + b
STFI, lb/inch; ring crush, lb/6inch.

In research carried out at the Institute we wet pressed experimental mediums made on the Formette former to varying degrees. The mediums were then fabricated into combined board on the Institute's pilot corrugator. Figures 14 and 15 show that increasing the medium density increased MD and CD STFI compressive strength. However, the ring crush results passed through a maximum at about 750-800 kg/m³ (density based on IPC compressible platen thickness gage). The ECT and flat crush strengths achieved with these mediums increased over the entire density range in the same way as the STFI compressive strength results (see Fig. 16 and 17). Thus the STFI results were more indicative of the fluted performance of the medium than ring crush. This occurs because ring crush is unduly influenced by the thickness changes accompanying densification via wet pressing. These results indicate that care must be used in selecting an appropriate compressive strength test when evaluating the potential effects of papermaking changes.

STFI COMPRESSIVE STRENGTH vs. ELASTIC STIFFNESSES

Recent research at the Institute indicates that compressive strength (ECS) is well related to the elastic properties (2). The relationship between compressive strength (ECS) and the elastic stiffnesses can take several forms which are believed to be equivalent at this time. The forms are

$$\text{MD} \quad \text{ECS} \propto (E_{xt})^{3/4}(E_{zt})^{1/4} \quad (4)$$

$$\propto (E_{xt})^{1/2}(G_{xz})^{1/2} \quad (5)$$

$$\propto (E_{xt})^{2/3}(E_{zt})^{1/6}(G_{xz})^{1/6} \quad (6)$$

$$\text{CD} \quad \propto (E_{yt})^{3/4}(E_{zt})^{1/4} \quad (7)$$

$$\propto (E_{yt})^{1/2}(G_{yz})^{1/2} \quad (8)$$

$$\propto (E_{yt})^{2/3}(E_{zt})^{1/6}(G_{yz})^{1/6} \quad (9)$$

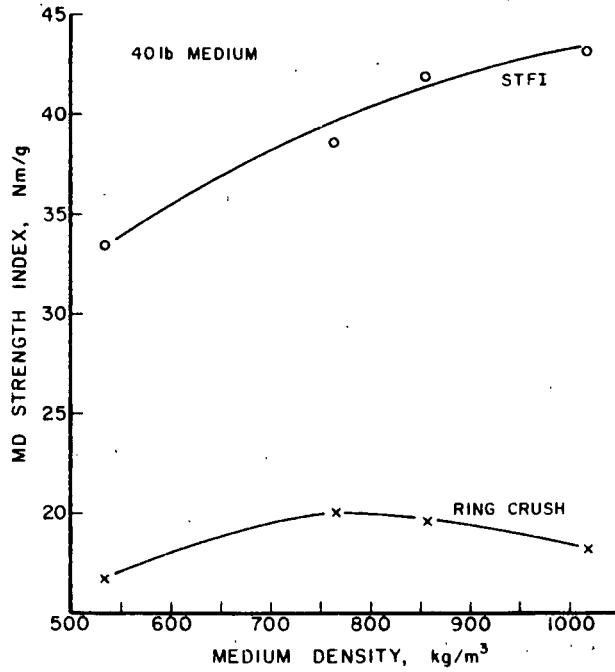


Figure 14. MD STFI and ring crush show different trends with increasing medium density.

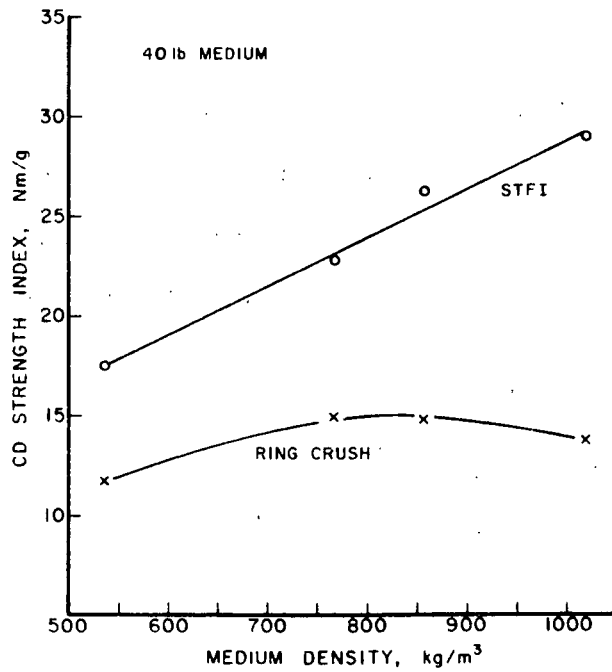


Figure 15. CD STFI and ring crush show different trends with increasing medium density.

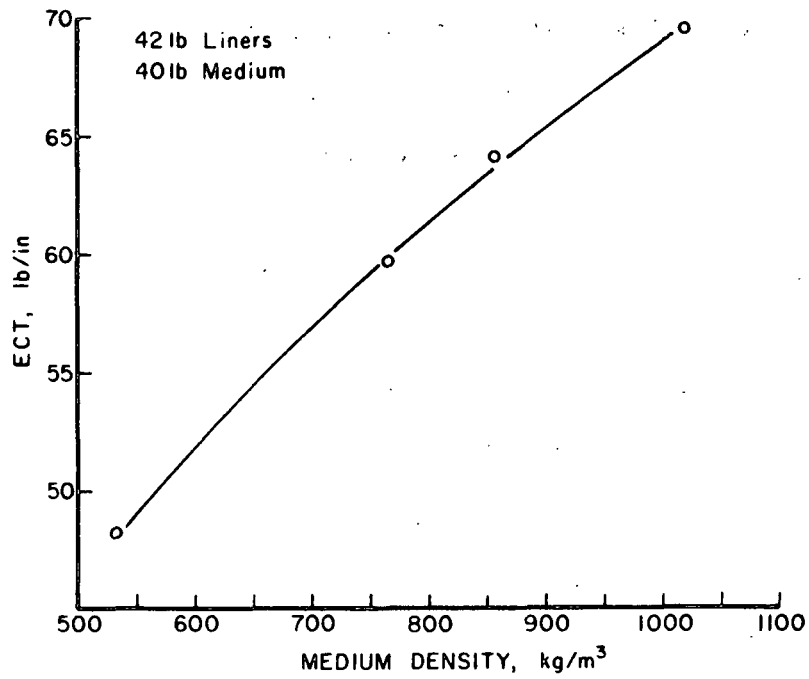


Figure 16. Wet pressing medium to higher densities increases the ECT of combined board.

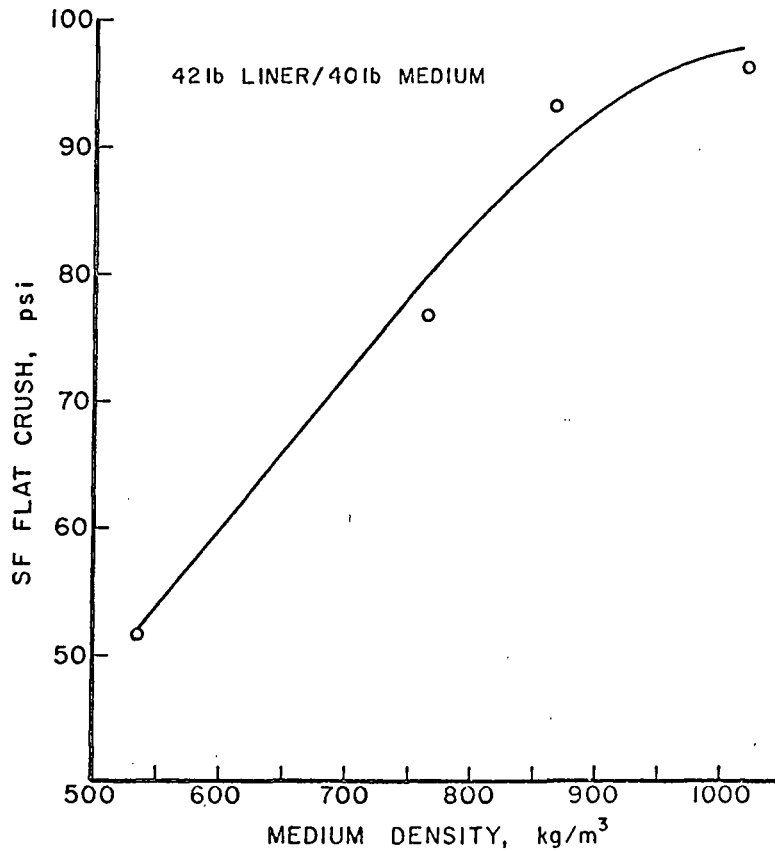


Figure 17. Wet pressing medium to higher densities increases the flat crush of combined board.

Thus compressive strength is favored by high in-plane and out-of-plane stiffnesses. In our work on this project we have favored Eq. (4) and (7) inasmuch as the alternate forms gave no better correlations. The product of these moduli is referred to as the elastic stiffness or model function in the following discussion.

Figure 18 illustrates the general relationships between STFI results and the elastic stiffnesses from Eq. (4) and (7) in relation to grade weight averages. Inspection of Fig. 18 indicates the elastic stiffness function is linearly related to STFI. There is a small difference between the MD and CD results which we have taken into account in our analyses. The reasons for this are not clear at this time.

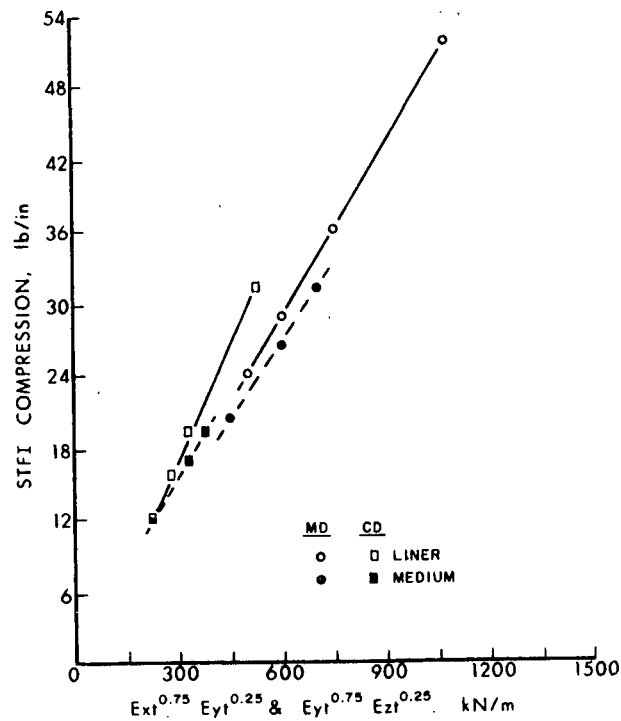


Figure 18. Relationship of CD STFI to elastic stiffness grade averages.

Relationships between STFI compression and elastic stiffnesses are summarized in Table 6 and 7 for the MD and CD directions, respectively. The individual grade weight correlations ranged from about 0.7 to 0.85 and the corresponding average prediction errors ranged from about 3.5 to 5.5%. Over all liner grades the correlation was 0.96 and for the medium, 0.95. The average overall prediction errors were about 6% for linerboard and 5% for the mediums.

Figures 19 and 20 illustrate the CD overall grade relations for the liner and medium, respectively. Figure 21 shows the within-grade relations for the 42-lb liners and 26-lb mediums.

Correlation coefficient magnitudes can be greatly affected by the range of values and test variability. Thus within-grade correlation coefficients are usually lower than obtained over a range of grade weights. One of the reasons is that material and test variability are a limiting factor as the range of values in the correlation is lowered. In the extreme, if there are no statistically significant variations in y and x , the correlation coefficient will usually be low and will approach zero. Even if there is a sound relationship between the two variables it can be obscured by test variability.

To provide information on what predictive accuracy could be expected we analyzed the variability of the elastic stiffnesses and the STFI test. Then, the odds of obtaining various levels of prediction accuracy from the regression equations were estimated. From this analysis we estimated that average prediction errors as large as 5-6% could be expected. Such estimated prediction errors are reasonably close to the values shown in Tables 6 and 7 for the experimental regressions. Thus the prediction accuracies of the experimental relationships seem to be approaching the inherent variability of the tests involved.

Table 6. MD STFI vs. elastic stiffness function.

Data	N	Regression Coefficients		R	Av. Prediction Error, %	% With Less Than 10% Error
		A(slope)	B(intercept)			
All liners	56	0.0472	0.4796	0.9649	5.985	87.5
26/33	20	0.0349	7.1625	0.8534	5.654	85.0
42	20	0.0276	14.8936	0.7387	3.969	95.0
69	16	0.0275	22.5236	0.6920	4.602	100.0
All mediums	49	0.0379	3.9178	0.9549	4.908	91.8
26	26	0.0279	7.9795	0.7562	3.645	100.0
33/36	13	0.0247	12.1395	0.7658	4.099	100.0
40/42	9	0.0221	16.1165	0.7628	3.980	88.9

Note: MD STFI (lb/inch) = A (E_{xt})^{0.75} (E_{zt})^{0.25} + B.
Stiffness units: kN/m.

Table 7. CD STFI vs. elastic stiffness function.

Data	N	Regression Coefficients		R	Av. Prediction Error, %	% Predictions Less Than 10%
		A(slope)	B(intercept)			
All liners	56	0.0541	1.2241	0.9636	6.925	71.4
26/33	20	0.0421	3.7123	0.8964	5.476	80.0
42	20	0.0364	7.1267	0.8758	4.160	95.0
69	16	0.0315	14.1016	0.8211	4.317	87.5
All Mediums	49	0.0459	2.1732	0.9555	5.225	87.8
26	26	0.0341	4.5641	0.7803	4.612	88.5
33/36	13	0.0367	5.3002	0.8116	4.385	92.3
40/42	9	0.0094	16.2283	0.2904	4.993	100.0

Note: CD STFI (lb/inch) = A (E_{yt})^{0.75} (E_{zt})^{0.25} + B.
Stiffness units: kN/m.

As another way of removing basis weight effects, the correlations were carried out on a unit weight basis, i.e., in terms of compressive index and specific elastic stiffnesses. These results are summarized in Tables 8 and 9. In general, the within grade correlation coefficients and prediction accuracies

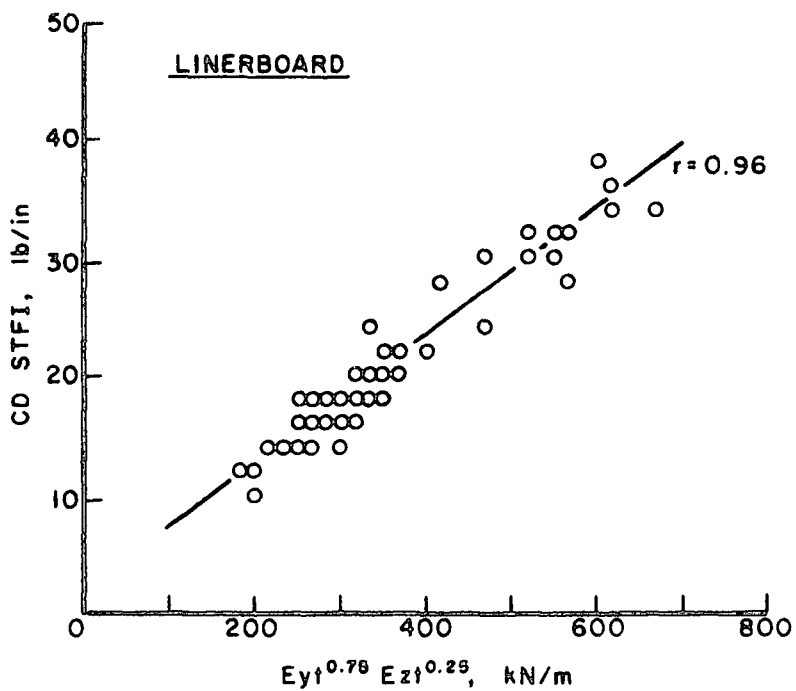


Figure 19. Relationship between CD STFI results and elastic stiffnesses for linerboard.

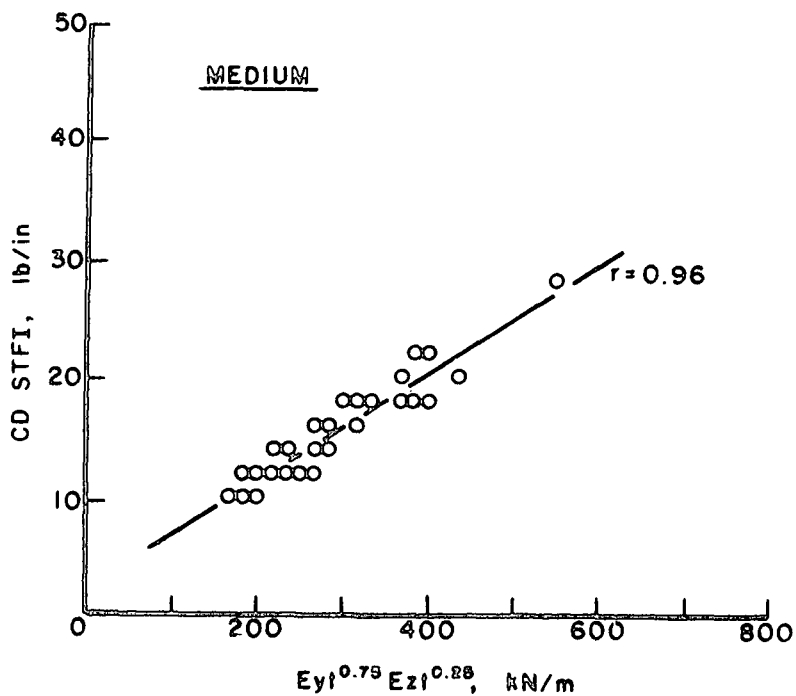


Figure 20. Relationship between CD STFI results and elastic stiffnesses for medium.

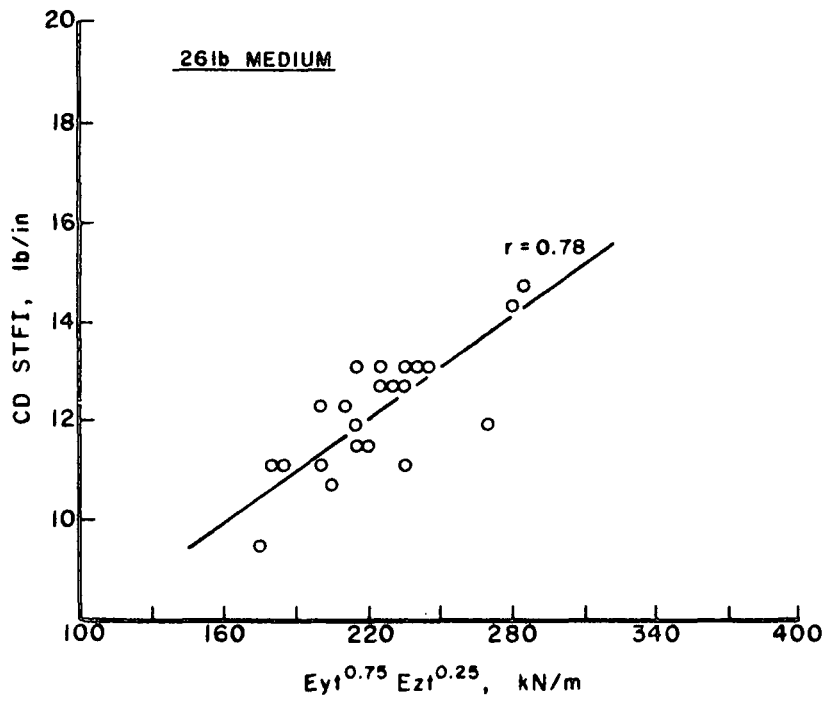
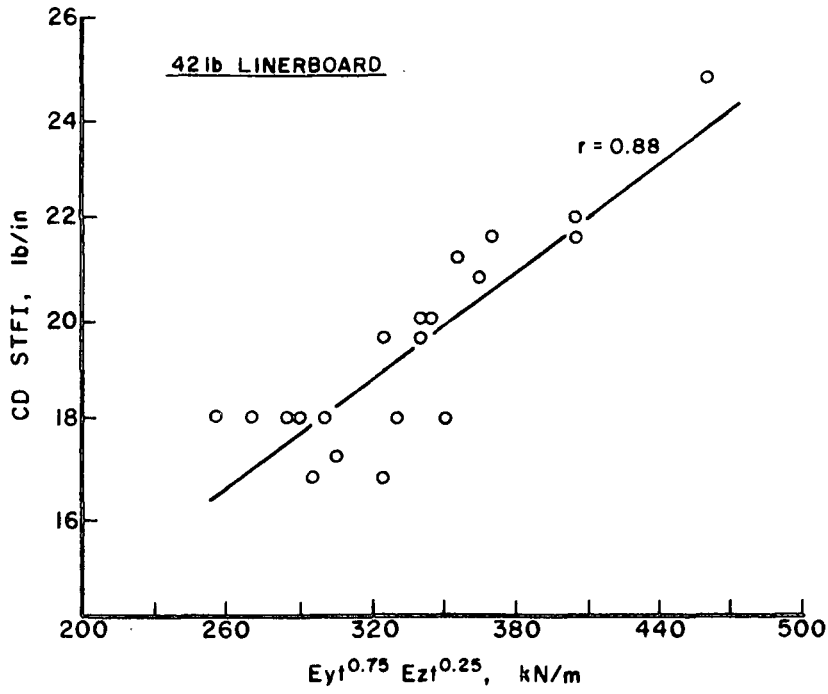


Figure 21. STFI results vs. elastic stiffnesses for 42-lb liners and 26-lb mediums.

were close to those obtained with the elastic stiffnesses. In both ways of analyzing the data it appears that we are approaching the limits imposed by material and test variability.

Table 8. MD STFI index vs. specific elastic stiffness function.

Data	N	Regression Coefficients		R	Av. Prediction Error, %	% Predictions Less Than 10%
		A(slope)	B(intercept)			
All liners	56	5.7169	9.2391	0.7936	5.132	85.7
26/33	20	5.5140	10.2190	0.7178	6.201	85.0
42	20	4.8774	12.4206	0.7017	4.317	95.0
69	16	4.4066	12.9066	0.6279	4.452	93.8
All mediums	49	3.9056	14.2331	0.6621	3.777	98.0
26	26	4.4549	12.3680	0.7255	3.404	100.0
33/36	13	4.1125	13.6234	0.6700	4.277	100.0
40/42	9	3.3598	15.9901	0.6198	3.943	88.9

Note: MD STFI Index (Nm/g) = A (E_x/ρ)^{0.75} (E_z/ρ)^{0.25} + B.
Specific stiffness units: MNm/kg.

Table 9. CD STFI index vs. specific elastic stiffness function.

Data	N	Regression Coefficients		Corr. Coeff. R	Av. Prediction Error, %	% Predictions Less Than 10%
		A(slope)	B(intercept)			
All liners	56	5.7957	6.8732	0.8256	4.673	87.5
26/33	20	5.9094	6.6227	0.7901	5.135	85.0
42	20	5.9680	6.6676	0.8408	4.272	90.0
69	16	5.6070	7.1503	0.8366	4.380	87.5
All mediums	49	5.5065	7.1044	0.7381	4.951	85.7
26	26	5.7340	6.6180	0.7819	4.507	84.6
33/36	13	6.0622	6.3049	0.7377	4.279	92.3
40/42	9	2.6527	12.4172	0.3347	6.399	77.8

Note: CD STFI Index (Nm/g) = A (E_y/ρ)^{0.75} (E_z/ρ)^{0.25} + B.
Specific stiffness units: MNm/kg.

Inspection of the elastic stiffness relations in Tables 6 and 7 suggests there may be systematic changes in the regression coefficients as grade weight changes. It may also occur in the specific stiffness relations though it is less evident. At this time we can only speculate in the causes. As one possibility there is some evidence that the STFI mode of failure changes from light to heavy weight materials. If so, this would complicate its relation to the elastic properties. The proposed instrumentation study of the STFI tester will provide an opportunity to investigate the failure mechanism in more detail. As another possibility the shear/Young's moduli relations used in the compressive strength model may be somewhat sensitive to basis weight. Such shift could make the experimental regression coefficients change with basis weight. It appears that further study is desirable to establish the cause for the behavior.

For the present we believe the overall grade relations in Tables 6 and 7 should be sufficient for most purposes.

RING CRUSH vs. ELASTIC STIFFNESSES

The ring crush test is inherently a more complex test than the STFI. Because of the fixed ring size and height there are differences in mode of failure from thin to thick materials. Also, the buckling and failure of cylindrical orthotropic structures is known to be sensitive to imperfections in geometry and presumably material (3). As one example, we know the free vertical ends weaken the test structure.

The buckling strength of a long orthotropic cylinder is dependent in the axial stiffness (E_t) in the direction of load, thickness, radius, and buckling coefficient (4). The latter is dependent on the ratio of axial to circumferential stiffness and another factor involving thickness, radius and also the

ratio of axial to circumferential stiffness. In cylinders of sandwich construction the buckling coefficient is complexly dependent on geometry, elastic in-plane properties and the out-of-plane properties, particularly the shear stiffness of the core, (5,6). Based on these considerations it would be expected that ring crush will be dependent on the following: in-plane elastic stiffness in axial and circumferential directions, the out-of-plane stiffnesses such as E_{zt} , $G_{xz}t$ and $G_{yz}t$, and the thickness or density of the sheet. Ring crush is known to pass through a maximum when density increases as discussed earlier.

For reasons such as these the ring crush grade averages in Fig. 22 show large differences between MD and CD direction when plotted against the compressive model function. There also appear to be some differences between liner and medium behavior.

After extensive analysis of alternates we related ring crush to linear combinations of the axial and circumferential stiffnesses. These were defined as follows:

	Axial	Circumferential
MD:	$E_{xt}^{0.75} E_{zt}^{0.25}$	$E_{yt}^{0.75} E_{zt}^{0.25}$
CD:	$E_{yt}^{0.75} E_{zt}^{0.25}$	$E_{xt}^{0.75} E_{zt}^{0.25}$

To provide more stable estimates of the importance of the two directions we analyzed the MD and CD direction data together. Figure 23 illustrates that consideration of both axial and circumferential stiffnesses essentially removes the MD and CD differences evident in Fig. 22.

Table 10 summarizes the relationships obtained with the liners and mediums. Two formulas are shown, one based on stiffness and the other on

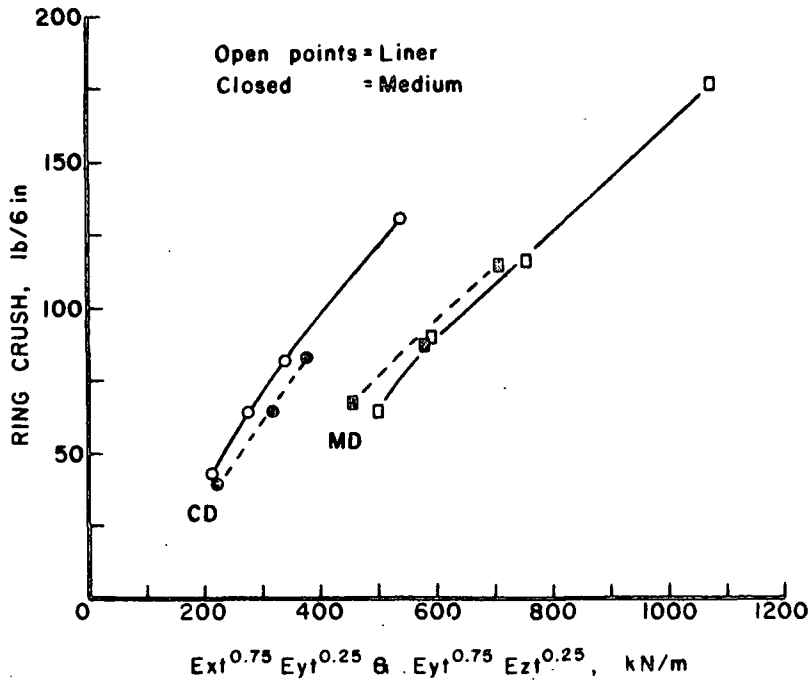


Figure 22. Ring crush results vs. elastic stiffness function in axial direction.

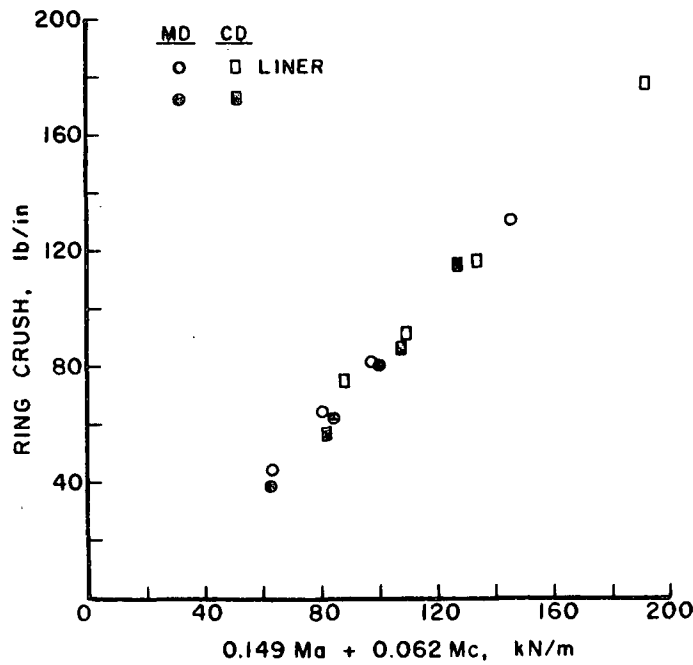


Figure 23. Ring crush results vs. elastic stiffness model functions in the axial (M_a) and circumferential (M_c) directions (M = E_t^{0.75} E_zt^{0.25}).

stiffnesses and density. The overall correlation coefficients are high and the prediction errors average around 7%. The prediction errors are probably near the variability in the measurements as discussed in the case of the STFI.

Figure 24 illustrates the agreement between predicted and observed ring crush values for the mediums.

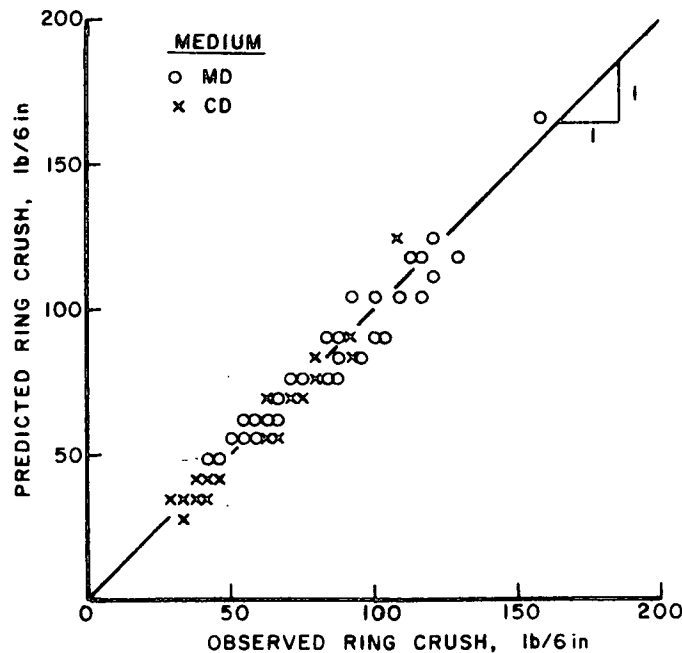


Figure 24. Observed vs. predicted ring crush values based on elastic stiffnesses in the two directions and density.

In the case of the medium, density was a significant factor and helped reduce prediction errors. It had a lesser effect in the case of the liners. We believe it should be kept in mind in both cases when large density differences occur.

These relationships reduce to three terms; namely,

1. stiffness function in direction of load, $E_t^{0.75} E_{zt}^{0.25}$,
where E_t denotes E_{xt} for MD and E_{yt} for CD direction

Table 10. Ring crush relationships.

	Regression Equation	Corr. Coeff.	Av. Prediction Errors %	% Error \leq 10%
All liners:				
1. MD:	$RC = 0.148 E_x t^{0.75} E_z t^{0.25} + 0.065 E_y t^{0.75} E_z t^{0.25} - 17.5$	0.975	7.3	75
CD:	$RC = 0.148 E_y t^{0.75} E_z t^{0.25} + 0.065 E_x t^{0.75} E_z t^{0.25} - 17.5$			
2. MD:	$RC = 0.147 E_x t^{0.75} E_z t^{0.25} + 0.064 E_y t^{0.75} E_z t^{0.25} - 0.0379 + 11.2$	0.976	6.9	79
CD:	$RC = 0.147 E_y t^{0.75} E_z t^{0.25} + 0.064 E_x t^{0.75} E_z t^{0.25} - 0.0379 + 11.2$			
All mediums:				
1. MD:	$RC = 0.149 E_x t^{0.75} E_y t^{0.25} + 0.062 E_y t^{0.75} E_z t^{0.25} - 21.6$	0.955	--	--
CD:	$RC = 0.149 E_y t^{0.75} E_z t^{0.25} + 0.062 E_x t^{0.75} E_z t^{0.25} - 21.6$			
2. MD:	$RC = 0.149 E_x t^{0.75} E_z t^{0.25} + 0.062 E_y t^{0.75} E_z t^{0.25} - 0.110 + 52.1$	0.975	6.9	75
CD:	$RC = 0.149 E_y t^{0.75} E_z t^{0.25} + 0.062 E_x t^{0.75} E_z t^{0.25} - 0.110 + 52.1$			

Notes: RC = Ring Crush, lb/6 inch.
 = Density based on IPC thickness, kg/m³.

$E_x t, E_y t$ = In-plane elastic stiffnesses, kN/m.
 $E_z t$ = Z direction elastic stiffness, kN/m.

2. a directionality function $(1 + K(E_{xt}/E_{yt})^{0.75})$
3. density.

For boards with about the same directionality and density the first is dominant. The second and third terms can be viewed as correction factors which come into play if there are large differences in directionality or density. From a theoretical standpoint we need a more rigorous analysis of the ring test to more precisely define the failure factors.

We have applied these equation forms to the 42-lb liner and the 26-lb medium data. The prediction errors are about 6%. The correlation coefficients are near 0.93 to 0.95. These are favorably high but influenced by using both MD and CD data in the correlation.

BURSTING STRENGTH

Bursting strength is primarily dependent on the average tensile strength of the board times the square root of the stretch in the machine direction. More refined analyses indicate the directionality of the board should be taken into account.

Because tensile strength is well related to the in-plane elastic stiffnesses, the average tensile should be approximately related to the geometric mean of the in-plane stiffnesses $[(E_{xt})(E_{yt})]^{1/2}$. The latter is well related to G_{xyt} as discussed earlier.

As might be expected from the above, bursting strength appeared to be best related to the in-plane shear stiffness (see Table 11). Initial efforts to include other stiffnesses indicated only small improvements could be gained. While an overall correlation coefficient of 0.94 was obtained, the within-grade

coefficients ranged from 0.40 to 0.57. We need to see if these can be improved, perhaps by consideration of MD stretch.

Table 11. Relationships between burst and the in-plane shear stiffness on linerboard.

	Corr. Coeff.	Std. Error of Estimate	Intercept, b	Slope, a
L 26-33	0.61	9.85	26.16	0.129
L 42	0.40	6.05	67.98	0.066
L 69	0.57	11.86	50.82	0.106
L 42-69	0.91	8.99	36.62	0.121
All	0.94	9.44	26.24	0.134

Note: $\text{Burst} = a G_{xy}t + b$.

COMBINED BOARD ECT

As mentioned previously, the liners were combined with a "standard" medium into single-faced board. They were then manually double-backed. Similarly, the mediums were combined with a "standard" liner. ECT tests were carried out on the double-faced boards.

For analysis purpose the ECT tests results were related to the component properties using simple addition formulas, i.e.,

$$\text{ECT} = a (2L + DM) + b$$

where L = CD liner property
 M = CD medium property
 D = draw factor
 a, b = constants

Test properties compared in this way include CD STFI, CD elastic stiffness function ($E_{yt}^{0.75} E_{zt}^{0.25}$) and ring crush. The overall and within-grade correlations are summarized in Table 12. Figures 25 and 26 illustrate the overall relations obtained using the STFI and elastic stiffnesses, respectively.

The overall correlations are high as would be expected for this basis weight range. All three component characteristics, STFI, ring crush, and the elastic stiffnesses, correlated about equally well.

The within-grade correlation comparisons vary for the three component tests. For the 42-lb linerboards the three were nearly equivalent. For the 26- and 33-lb medium combinations the STFI results gave the highest correlations while ring crush was poor in both cases. Tentatively, it appears that

1. STFI tests correlate well with ECT. The ring crush correlations were high for the liner combinations but less so for the medium combinations.
2. The elastic stiffnesses of the components also correlate with ECT, which lends support to their use in measurement and control of board properties.

To predict ECT from STFI results the formula based on the combined liner and medium data should be used.

$$ECT = 0.685 (2S_1 + D S_m) + 4.62$$

where ECT = C.B. edge crush, lb/inch
 S_1 = CD liner STFI compressive strength, lb/inch
 S_m = CD medium STFI compressive strength, lb/inch
D = draw or take-up factor. Typical draw factors for A, B and C flute board are 1.56, 1.36 and 1.42, respectively.

Table 12. ECT correlations using simple summation model.

Data	CD Elastic Stiffnesses			CD STFI			CD Ring Crush		
	Corr. Coeff.	Intercept, b	Slope, a	Corr. Coeff.	Intercept, b	Slope, a	Corr. Coeff.	Intercept, b	Slope, a
All liners (47)	0.961	1.07	0.0410	0.967	2.60	0.705	0.978	9.00	0.966
26 & 33 (19)	0.780	9.79	0.0310	0.803	5.90	0.641	0.939	11.80	0.888
42 (14)	0.840	19.47	0.0238	0.824	6.03	0.646	0.814	13.30	0.830
69 (14)	0.720	13.80	0.0327	0.693	3.39	0.697	0.815	-0.64	1.150
All mediums (38)	0.955	16.21	0.0292	0.951	8.28	0.639	0.941	16.55	0.743
26 (19)	0.650	12.61	0.0329	0.726	6.71	0.666	0.543	17.80	0.705
33 (11)	0.842	14.12	0.0313	0.853	-7.44	0.891	0.450	20.41	0.657
All lots (85)	--	--	--	0.960	4.62	0.685	--	--	--

Notes: Model form: $ECT = a [2L + DM] + b$.
 ECT in lb/inch.
 Elastic stiffnesses in kN/m.
 STFI in lb/inch.
 Ring crush in lb/6 inch.

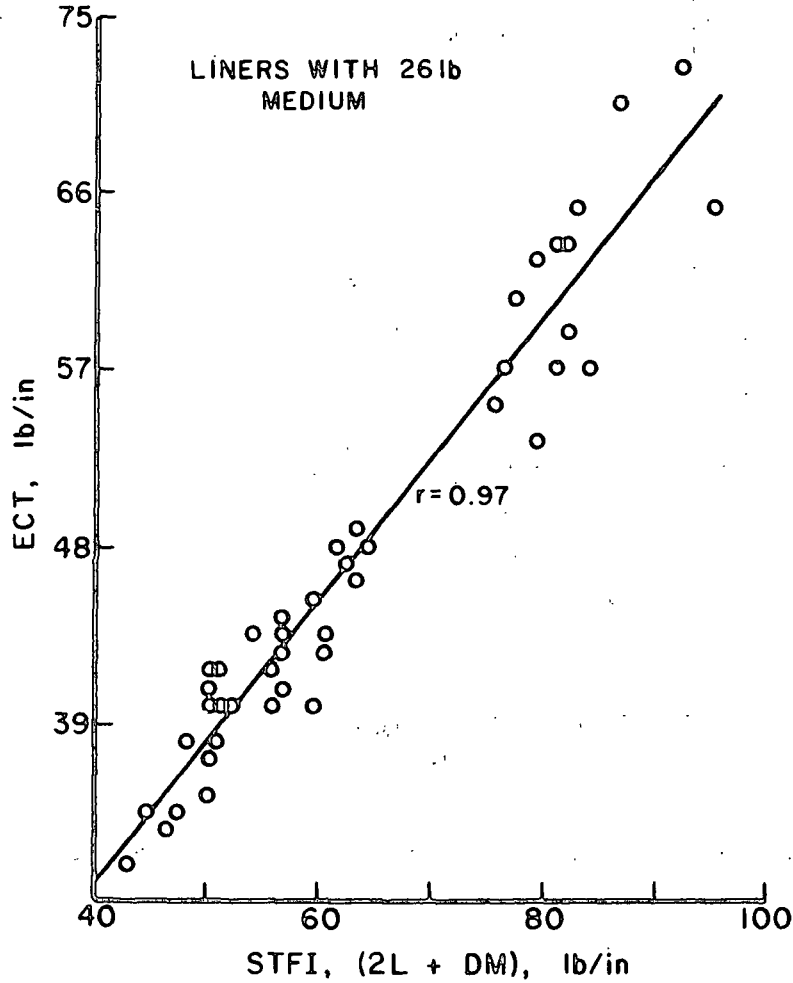


Figure 25. Relation between STFI and ECT for liner combinations.

The above ECT formula was cross checked by substituting STFI for ring crush in the Project 3511 formulas (7) using the relationships below. The resulting predictions were in good agreement with those obtained with the above formula.

STFI/ring crush formulas

Linerboard:

26-33: $S = 0.160 RC + 5.37$

42-69: $S = 0.234 RC + 0.148$

Medium:

26-40: $S = 0.183 RC + 5.20$

where $S = CD$ STFI, lb/in
 $RC = CD$ ring crush

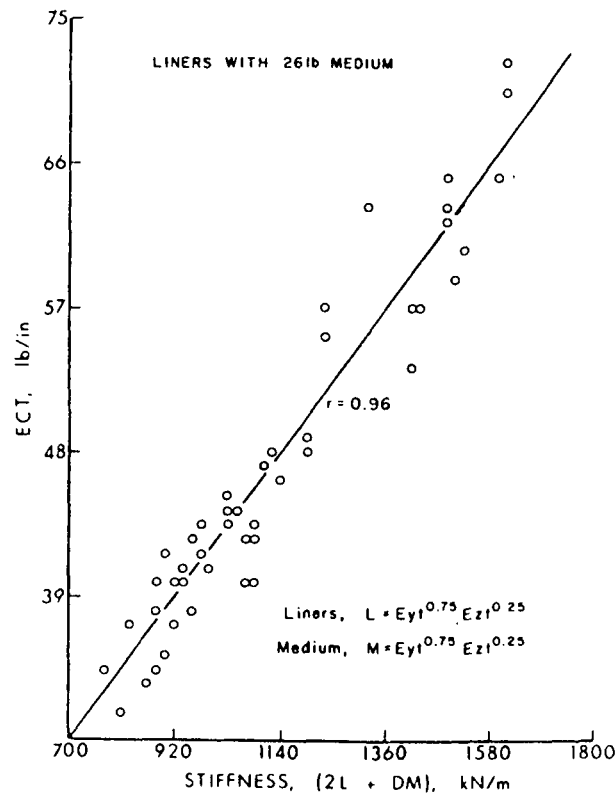


Figure 26. Relation between ECT and elastic stiffnesses for liner combinations.

CONCORA AND COMBINED BOARD FLAT CRUSH

Inspection of the combined board flat crush results indicates that the heavyweight mediums exhibit low flat crush strengths per pound of basis weight (see Table 13). For example, the 40 to 42-lb mediums are about 20% low on a pound of fiber basis. Some of the 33 to 36-lb mediums may exhibit similar behavior. This is not surprising because heavyweight mediums are usually more difficult to form without damage.

Examination of load-deformation curves suggests that such 40-lb mediums fail as the second arch begins to collapse (Fig. 27) They apparently do not square-off completely at failure in the typical "hat" shaped manner and hence do not attain as high a load as expected. A few photomicrographs of failed

specimens show severe delamination of the heavyweight mediums, although this can be seen on 26-lb samples too.

Table 13. Combined board flat crush results.

Grade	Av. No. of Lots	Medium wt., lb/1000 ft ²	Flat Crush, psi	Flat Crush per Unit Weight, psi/lb
26	21	26.3	35.0	1.33
33-36	11	34.0	44.6	1.31
40-42	7	40.9	43.7	1.07
52	1	54.2	45.3	0.84

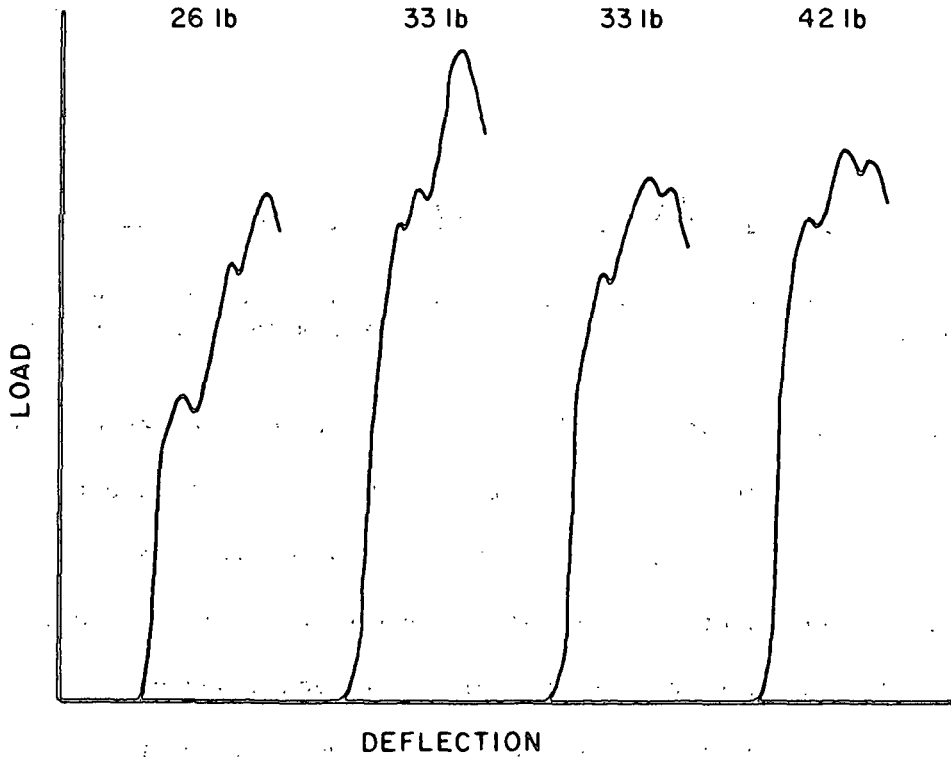


Figure 27. Flat crush load-deformation curves showing that heavy weight mediums fail as second arch begins to collapse.

Figure 28 shows pressure patterns obtained when materials of increasing thickness are corrugated on C-flute rolls. At calipers in the 8.5 to 11 mil range the maximum pressures during corrugating are exerted on the flute tips as expected. However, at the higher calipers most of the corrugated roll pressure is imposed on the flute sidewalls. As a consequence the flute flanks suffer more caliper loss and greater fiber-to-fiber bonding damage as medium weight and caliper increase. This lowers the ultimate flat crush strength of the flute.

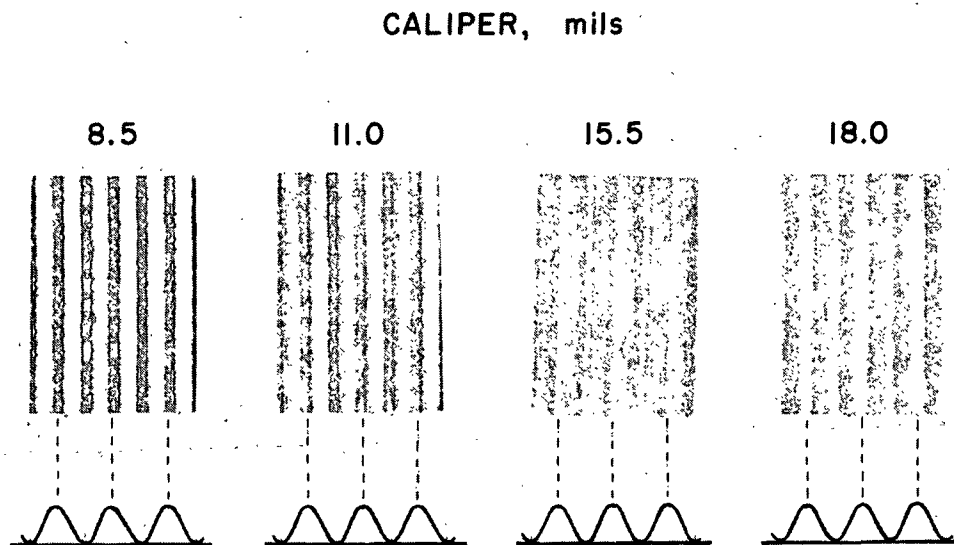


Figure 28. C-flute corrugating pressure patterns show corrugating pressures shift from flute tips to flanks as medium caliper increases.

Changes in flute profile to introduce more flank clearance while maintaining or increasing the flute tip radii may be one way to improve the runnability of high weight medium. Another approach is to densify the medium by means of wet pressing which will lower caliper and increase most strength properties for the same basis weight. In our current funded research program we have shown that high flat crush and ECT results are achieved by this approach.

In carrying out the Instron flat crush load-deformation tests we used the Instron peak detector computer system to measure initial peak loads. These

correspond to the first peak in the curves when the arches on one side collapse. The first peak loads (and deflections) are believed to be a better measure of the potentials of the board to resist conversion damage. Keeping in mind that not all curves show clearly visible first peaks, Table 14 shows that the first peak and ultimate flat crush loads exhibit opposite trends per pound of fiber.

Table 14. Comparison of ultimate and first peak flat crush loads per pound of fiber.

Grade	No. of Lots	Medium wt., lb/1000 ft ²	Load per Pound of Fiber		Defl, in first peak
			First Peak	Final Peak	
26	21	26.3	0.77	1.33	0.021
33-36	11	34.0	0.94	1.31	0.023
40	7	40.9	0.98	1.07	0.024

The 26-lb mediums exhibit a low first peak load but achieve relatively high final peak strengths per pound of fiber. The higher weight mediums show higher first peak strengths, but their final peak strengths per pound of fiber decrease due to flank damage. However, the deflections at first peak show little change with increasing weight. Thus for a given degree of crushing deformation during conversion the higher medium weights retain an advantage.

The fluting damage which affected flat crush results does not seem to affect ECT results in the same way. Table 15 shows that ECT results per pound of combined board weight are constant for the various medium grade weights. The ECT results do decrease if based on the medium weight.

The ultimate flat crush strengths of the 26- and 33 to 36-lb grade medium combinations were fairly well related to Concora and MD STFI compressive strength (see Fig. 29 and 30). Flat crush also appeared about equally well

related to the elastic stiffnesses, E_{xt} and E_{zt} . However, the STFI and elastic stiffness relationships appeared to be sensitive to the flute damage incurred in corrugating the heavier weight mediums. The Concora appeared to be less sensitive to flute damage because it simulates in part the fluting process.

Table 15. ECT results for medium combinations with 42-lb liner.

Av. Medium Weight, lb/1000ft ²	No. of Lots	Av. ECT, lb/inch	ECT/lb of Fiber	
			Based on C.B. wt.	Based on Medium wt. ^a
26.3	21	43.0	0.35	1.15
34.0	11	47.9	0.35	0.99
40.9	7	50.5	0.35	0.87

^aMultiplied by draw factor (1.42).

Table 16. Flat crush correlations with medium properties (26 to 36-lb medium).

Independent Variable(s)	Regression Slope	Coefficients Intercept	Corr. Coeff.
1. Concora	0.49	4.43	0.92
2. MD STFI	1.53	3.55	0.81

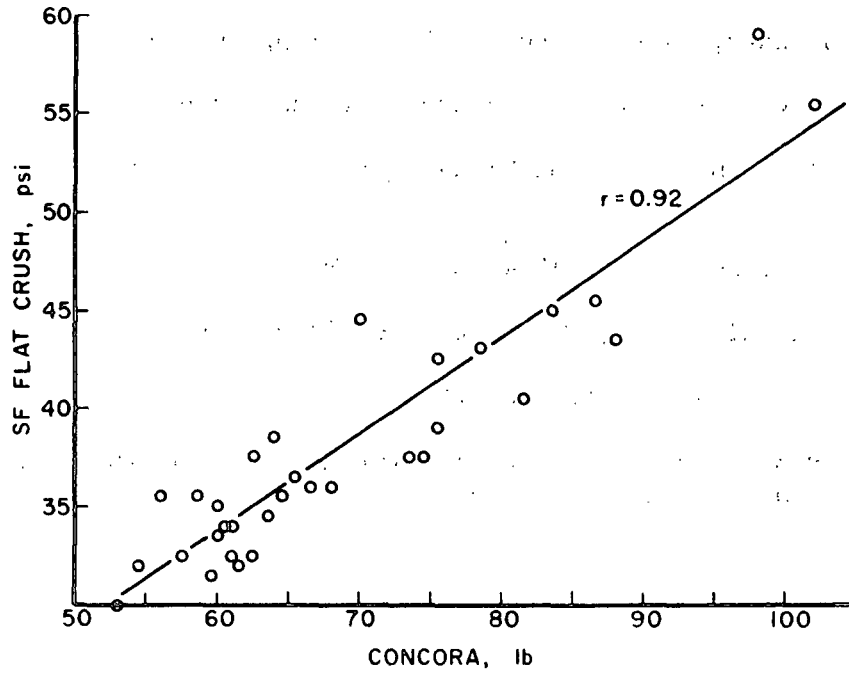


Figure 29. Relationship between Concora and C.B. flat crush.

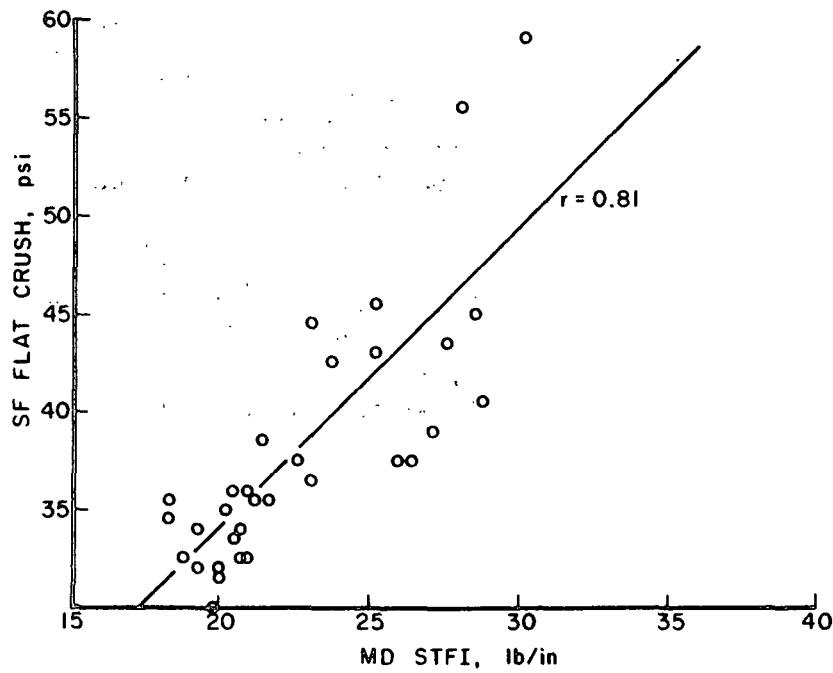


Figure 30. Relationship between MD STFI and C.B. flat crush.

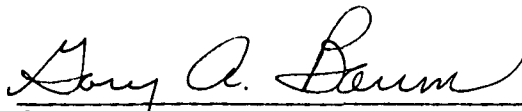
LITERATURE CITED

1. Baum, G. A.; Brennan, D. C.; Habeger, C. C., Tappi 64(8):97(Aug., 1981).
2. Habeger, C. C.; Whitsitt, W. J., Fibre Sci. and Technology 19:215-239(1983).
3. Brush, D. O.; Almroth, Bo O. Buckling of Bars, Plates, and Shells. McGraw Hill Book Co., 1975.
4. Kuenzi, E. W., FPL Report No. 1514, Revised March, 1984
5. March, H. W.; Kuenzi, E. W., FPL Report No. 1830, Revised Dec., 1957.
6. Norris, C. B.; Zahn, J. J., FPL Report No. 1876, July 1960.
7. Project 3511, Report Two to the Fourdrinier Kraft Board Group of the API and Fibre Box Association, Feb. 18, 1983.

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APPENDIX I

TEST RESULTS

Strength Properties of Linerboard (Tables 17 - 20)

Strength Properties of Medium (Tables 21 -24)

Elastic Stiffness Results (Tables 25 - 32)

Combined Board Test Results (Tables 33 and 34)

Table 17. Strength properties for 26-lb liner.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil	STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi	
		TAPPI	IPC									
101	26.3	8.01	6.50	3.287	4.051	24.99	11.77	64.6	37.5	15.8	7.9	74.3
141	28.9	7.79	6.31	3.714	4.582	28.50	13.08	63.0	44.7	14.0	6.9	71.9
241	26.7	8.3	7.0	3.186	3.808	18.78	10.81	58.4	39.4	14.3	8.5	67.2
261	26.6	7.4	6.	3.34	3.89	23.35	13.37	68.7	51.0	18.8	7.9	80.1
291	26.9	8.74	7	3.06	3.78	24.14	12.37	66.9	45.3	17.2	7.0	72.5
Average	27.1	8.17	6.76	3.322	4.015	23.95	12.28	64.3	43.6	16.0	7.6	73.2
Std. dev.	1.0	0.38	0.36	0.242	0.338	3.50	1.03	4.0	5.3	2.0	0.7	4.7
CV	3.9	4.7	5.3	7.3	8.4	14.6	8.4	6.2	12.2	12.6	9.0	6.4

Note: CV = coefficient of variation (percent standard deviation).

Table 18. Strength properties for 33-lb liner.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil		STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC	TAPPI	IPC							
61	33.2	9.99	8.47	3.322	3.916	26.68	14.55	89.3	65.2	27.9	13.3	74.4
102	33.3	10.54	8.95	3.160	3.721	31.32	14.55	92.5	61.5	38.6	17.5	84.9
111	34.5	10.31	8.80	3.344	3.919	32.42	17.95	113.3	79.7	38.6	16.8	100.4
142	34.9	9.50	8.10	3.673	4.307	26.42	13.76	83.37	55.5	24.7	13.6	75.3
151	32.9	10.40	8.86	3.161	3.711	28.08	15.11	90.0	61.5	32.0	15.1	79.1
161	33.3	10.22	8.36	3.257	3.980	29.34	14.92	91.3	66.2	38.8	15.4	82.8
171	33.3	10.23	8.63	3.254	3.859	26.30	15.00	86.3	60.3	34.3	11.0	97.3
181	34.0	11.56	9.43	2.938	3.602	29.17	19.68	83.4	62.0	32.9	18.5	78.3
192	34.8	11.03	9.19	3.151	3.783	28.04	14.65	85.8	58.8	37.2	16.0	77.4
201	33.9	11.57	10.14	2.927	3.339	29.63	15.62	96.2	60.9	59.8	19.6	92.4
214	35.1	10.11	8.44	3.474	4.163	35.34	18.20	111.4	76.3	41.4	23.3	118.7
242	32.8	9.82	8.43	3.341	3.896	23.09	17.67	81.5	68.6	23.0	18.6	74.9
262	33.6	10.27	8.81	3.272	3.812	24.28	14.82	80.7	57.5	32.0	15.5	86.1
292	33.7	10.86	9.10	3.101	3.701	31.80	15.45	96.4	69.4	32.4	18.2	91.6
321	34.2	9.19	8.65	3.723	3.958	27.07	14.65	71.1	54.0	38.3	18.7	83.8
Average	33.8	10.37	8.82	3.273	3.844	28.60	15.77	90.2	63.8	35.5	16.7	86.5
Std. dev.	0.7	0.67	0.50	0.226	0.229	3.22	1.73	11.1	7.2	8.6	3.0	12.1
CV	2.2	6.4	5.7	6.9	6.0	11.3	11.0	12.3	11.4	24.3	16.9	14.0

Note: CV = coefficient of variation (percent standard deviation).

Table 19. Strength properties for 42-lb liner.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil TAPPI	IPC	STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC									
62	43.7	12.86	11.21	3.400	3.900	36.67	21.42	131.2	93.4	65.6	29.8	111.1
81	41.6	11.43	9.92	3.638	4.190	34.60	19.79	121.9	83.5	52.0	24.2	106.3
103	42.8	11.51	9.88	3.715	4.330	40.88	21.01	137.0	93.9	59.2	25.7	109.6
112	42.1	12.43	10.81	3.386	3.892	37.46	19.53	123.3	86.3	67.8	31.9	119.6
143	41.8	11.53	9.47	3.624	4.412	37.83	21.81	111.5	81.2	41.0	24.0	97.8
152	42.2	13.55	11.98	3.111	3.519	31.38	17.95	102.7	75.3	71.0	31.9	110.9
162	43.8	12.77	11.35	3.428	3.856	34.95	18.13	107.9	75.3	71.0	31.8	98.1
172	42.2	12.51	11.30	3.375	3.737	34.08	18.10	108.2	78.6	70.2	19.4	100.1
182	41.7	13.47	11.70	3.098	3.568	31.54	16.70	102.7	73.7	68.8	28.6	102.5
193	43.9	13.00	11.06	3.377	3.966	39.80	20.64	130.1	91.1	78.2	38.0	113.5
202	41.6	13.67	12.27	3.048	3.394	35.10	17.95	106.8	73.5	108.5	36.6	115.7
212	42.3	13.54	10.98	3.126	3.853	38.09	16.90	119.9	71.8	79.2	28.6	96.1
243	42.5	11.16	9.88	3.810	4.303	35.09	21.57	122.2	91.3	46.4	27.0	102.9
251	42.9	11.94	10.84	3.592	3.954	40.23	17.81	122.2	76.3	72.2	25.7	105.4
263	42.5	12.04	10.65	3.535	3.995	35.55	19.87	119.4	80.2	63.2	24.1	103.9
273	44.6	12.32	10.75	3.618	4.146	32.83	24.81	127.1	100.0	57.0	37.5	113.1
281	42.5	12.39	10.94	3.435	3.889	32.43	17.97	110.8	71.3	64.2	28.9	101.1
293	42.6	12.39	11.01	3.441	3.871	35.70	19.43	116.0	84.2	68.4	32.5	104.5
311	40.1	12.43	11.06	3.223	3.624	34.99	18.00	103.6	73.5	66.8	30.5	101.7
322	41.5	11.35	10.75	3.658	3.861	34.61	17.14	88.8	67.7	72.2	30.6	105.4
Average	42.4	12.41	10.89	3.432	3.913	35.69	19.33	115.7	81.1	67.1	29.4	106.0
Std. dev.	1.0	0.78	0.70	0.222	0.270	2.72	2.06	11.9	9.0	13.8	4.8	6.4
CV	2.4	6.3	6.5	6.5	6.9	7.6	10.7	10.3	11.1	20.5	16.4	6.1

Note: CV = coefficient of variation (percent standard deviation).

Table 20. Strength properties for 69-lb liner.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil		STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC	TAPPI	IPC							
63	70.2	21.29	18.81	3.296	3.730	56.05	33.20	207.3	146.9	321.5	133.0	138.8
82	68.2	19.59	17.67	3.482	3.860	49.96	30.62	167.2	130.8	235.5	115.0	128.3
113	68.3	21.36	18.81	3.199	3.632	48.15	29.26	170.9	123.2	255.5	109.0	146.2
144	68.6	20.70	18.66	3.315	3.679	48.15	28.47	165.5	131.4	226.5	103.8	134.9
173	67.8	19.51	17.82	3.478	3.808	51.24	31.11	183.4	142.2	258.0	101.6	142.1
183	70.5	22.64	20.71	3.116	3.405	47.78	27.60	158.5	114.2	311.0	142.5	125.2
194	70.7	21.61	19.14	3.274	3.697	46.47	30.99	173.8	126.8	254.5	142.0	164.2
203	68.4	21.47	19.91	3.185	3.434	50.16	28.23	165.7	116.0	357.0	125.5	137.4
213	68.9	21.11	18.32	3.263	3.759	54.02	31.22	187.7	136.5	280.0	121.0	158.5
225	73.0	22.06	19.80	3.308	3.687	60.33	23.47	178.4	108.3	369.0	80.5	125.6
244	70.2	20.11	18.47	3.491	3.801	50.29	31.78	159.8	129.3	213.0	107.4	140.7
252	67.8	20.11	18.63	3.372	3.639	56.06	30.49	182.8	126.9	303.0	115.0	154.8
274	71.6	21.52	19.62	3.325	3.647	52.14	36.02	191.6	142.7	300.0	146.0	161.9
282	68.1	17.63	16.01	3.863	4.254	47.92	33.12	176.8	134.2	184.5	93.4	150.7
294	69.6	17.75	16.60	3.923	4.194	57.23	37.44	200.1	152.1	231.0	104.0	168.2
312	67.9	19.76	18.34	3.438	3.704	51.36	29.73	163.6	114.1	265.0	109.6	132.1
Average	69.4	20.51	18.58	3.396	3.746	51.71	30.80	177.1	129.7	272.8	115.6	144.4
Std. dev.	1.5	1.43	1.19	0.223	0.222	3.99	3.30	14.3	12.6	51.3	18.5	14.0
CV	2.2	6.9	6.4	6.6	5.9	7.7	10.7	8.1	9.7	18.8	16.0	9.7

Note: CV = coefficient of variation (percent standard deviation).

Table 21. Strength properties for 26-lb medium.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil TAPPI	Density, lb/ream-mil		STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi	
			TAPPI	IPC								
11	26.6	10.55	7.63	2.522	3.485	19.48	11.98	54.2	38.9	14.8	6.1	55.4
12	26.4	10.55	7.71	2.503	3.425	18.34	11.55	51.8	36.4	14.0	7.5	56.2
21	26.6	9.85	7.54	2.704	3.535	21.14	10.99	54.8	37.7	14.2	5.5	64.4
31	26.2	10.02	7.55	2.619	3.474	19.77	10.99	52.6	35.6	14.7	5.0	60.7
41	26.8	9.97	7.36	2.684	3.635	20.56	10.58	55.4	32.2	16.8	5.8	68.0
42	26.5	10.03	7.25	2.638	3.652	21.44	10.87	57.1	31.3	16.7	5.4	63.8
51	26.6	10.56	8.01	2.524	3.325	21.00	12.77	62.5	42.2	16.7	9.0	61.1
71	26.4	11.43	7.13	2.308	3.701	18.37	12.85	41.8	33.7	10.7	11.5	63.5
91	26.9	11.06	8.19	2.428	3.281	22.58	11.06	63.8	40.8	23.7	7.0	62.7
121	26.3	11.66	7.54	2.259	3.493	20.18	13.11	58.3	42.2	17.9	6.5	59.8
122	26.2	11.93	7.52	2.197	3.482	19.92	13.07	55.2	41.0	15.3	8.3	59.7
123	26.4	11.61	7.54	2.273	3.497	20.76	12.83	56.0	40.6	15.7	8.3	57.4
124	26.5	12.14	7.56	2.181	3.502	21.43	12.46	59.2	42.1	14.3	7.0	58.2
125	26.3	12.15	7.48	2.167	3.522	19.16	12.72	53.1	40.5	15.8	8.3	60.9
126	26.4	12.07	7.54	2.185	3.499	20.52	13.16	56.9	41.6	15.0	6.4	60.1
127	26.3	11.57	7.52	2.276	3.503	19.85	12.62	58.2	42.1	14.2	6.7	61.7
131	26.4	8.98	6.98	2.944	3.786	20.85	14.31	58.9	45.9	13.4	6.1	66.6
184	26.4	10.44	7.61	2.526	3.466	23.20	12.20	62.2	42.2	17.4	7.0	69.9
191	26.5	9.15	7.33	2.897	3.618	23.21	11.97	66.6	42.3	19.4	10.3	65.5
211	25.0	9.85	6.65	2.540	3.764	19.70	11.97	50.4	38.7	13.5	8.4	52.9
221	26.3	10.03	7.19	2.627	3.660	21.58	9.43	58.9	29.1	19.2	7.9	58.4
231	25.9	9.36	6.44	2.770	4.024	19.38	11.39	43.9	32.7	10.7	4.6	54.4
271	27.0	9.02	6.67	2.995	4.050	22.88	14.61	55.7	39.5	15.6	13.3	72.1
295	26.9	10.40	7.80	2.586	3.447	22.57	12.96	66.4	44.5	18.8	8.3	66.6
301	25.0	10.35	8.03	2.420	3.118	18.78	12.05	54.4	40.0	14.0	7.1	62.5
302	26.6	10.38	8.11	2.567	3.285	20.59	12.50	59.7	41.6	14.4	9.7	60.4
Average	26.4	10.58	7.46	2.513	3.547	20.66	12.19	56.5	39.1	15.7	7.6	61.7
Std. dev.	0.5	0.98	0.43	0.238	0.207	1.42	1.14	5.8	4.3	2.7	2.0	4.7
CV	1.7	9.3	5.8	9.5	5.8	6.9	9.4	10.2	10.9	17.5	26.6	7.6

Note: CV = coefficient of variation (percent standard deviation).

Table 22. Strength properties for 33 to 36-lb medium.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil	TAPPI	IPC	STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC										
13	35.0	12.66	9.57	2.765	3.658	26.51	16.67	16.67	85.4	62.5	34.5	14.2	73.6
22	33.4	12.38	9.60	2.695	3.474	27.54	15.23	15.23	86.7	59.8	34.9	13.0	88.2
32	33.0	12.11	9.59	2.724	3.441	23.21	13.85	13.85	75.2	53.1	26.7	11.0	67.6
52	33.2	13.28	9.84	2.498	3.373	25.28	16.19	16.19	84.8	59.0	29.4	19.5	78.4
72	33.0	14.84	9.65	2.227	3.425	23.71	16.84	16.84	72.4	53.7	23.7	21.6	75.6
92	33.1	13.68	10.64	2.423	3.115	26.65	14.74	14.74	87.7	59.9	41.4	14.9	81.7
128	33.0	13.92	9.81	2.368	3.361	25.85	17.02	17.02	89.2	66.3	32.4	14.0	74.3
132	33.0	11.29	8.82	2.919	3.736	28.62	17.17	17.17	85.9	67.4	27.6	11.2	83.5
185	34.2	13.13	9.78	2.604	3.496	28.73	17.79	17.79	98.4	69.6	37.4	17.5	81.5
232	33.0	10.65	8.07	3.104	4.093	27.96	18.19	18.19	83.3	59.8	22.1	14.5	101.9
303	33.5	13.20	10.45	2.538	3.205	25.17	17.12	17.12	87.4	63.7	30.9	14.9	86.5
53	37.0	14.53	11.06	2.550	3.347	27.05	17.88	17.88	90.1	69.1	43.4	20.9	75.3
233	35.5	12.14	8.79	2.922	4.036	30.33	19.80	19.80	96.1	68.1	29.8	11.9	98.2
Average	33.8	12.91	9.67	2.641	3.520	26.66	16.81	16.81	86.4	62.5	31.9	15.3	82.0
Std. dev.	1.3	1.21	0.80	0.247	0.291	2.03	1.56	1.56	7.1	5.5	6.4	3.5	9.8
CV	3.7	9.4	8.2	9.3	8.3	7.6	9.3	9.3	8.2	8.8	20.0	23.0	12.0

Note: CV = coefficient of variation (percent standard deviation).

Table 23. Strength properties for 40 to 42-lb medium.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil		STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC	TAPPI	IPC							
54	41.2	15.95	12.20	2.584	3.377	32.40	20.07	111.8	83.1	54.8	31.8	77.7
73	39.5	17.09	11.86	2.311	3.331	28.16	19.39	101.1	74.8	44.6	29.2	77.1
93	40.4	16.80	13.18	2.405	3.064	32.41	18.73	121.0	78.3	71.0	23.5	90.0
129	39.4	16.22	11.89	2.430	3.314	31.63	21.20	117.0	89.9	49.2	26.8	90.9
222	39.5	13.40	10.66	2.949	3.706	31.67	18.67	110.1	69.4	54.2	22.0	85.4
223	42.5	14.83	11.44	2.869	3.716	30.11	18.28	115.4	78.4	59.6	27.4	80.0
272	41.0	14.60	11.53	2.806	3.553	35.55	22.06	129.3	85.6	63.6	34.3	82.6
304	40.0	15.81	13.22	2.530	3.025	27.72	20.72	104.5	83.9	54.6	27.5	78.1
186	43.7	16.22	12.68	2.696	3.447	34.60	18.92	122.7	90.2	61.6	32.8	78.3
Average	40.8	15.65	12.07	2.620	3.393	31.58	19.78	114.8	81.5	57.0	28.4	82.2
Std. dev.	1.5	1.17	0.84	0.223	0.246	2.62	1.31	9.0	6.9	7.9	4.1	5.4
CV	3.7	7.5	7.0	8.5	7.3	8.3	6.6	7.8	8.5	13.9	14.5	6.5

Note: CV = coefficient of variation (percent standard deviation).

Table 24. Strength properties for 52-lb medium.

Lot No.	Basis Wt., lb/1000 sq ft	Caliper, mil		Density, lb/ream-mil	STFI MD, lb/inch	STFI CD, lb/inch	Ring MD, lb/6 inches	Ring CD, lb/6 inches	Taber MD, g-cm	Taber CD, g-cm	Burst, psi
		TAPPI	IPC								
224	54.2	18.91	15.23	2.866	41.22	27.47	159.3	108.1	162.5	56.2	75.5
Average	54.2	18.91	15.23	2.866	41.22	27.47	159.3	108.1	162.5	56.2	75.5
Std. dev.	0.0	0.00	0.00	0.000	0.00	0.00	0.0	0.0	0.0	0.0	0.0
CV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: CV = coefficient of variation (percent standard deviation).

Table 25. Elastic stiffnesses (Et or Gt) 26-lb liner.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
101	1524.6	464.1	336.7	14.792	16.866	13.988	3.285
141	1805.0	540.6	393.6	20.286	18.439	15.726	3.339
241	1629.8	589.5	346.9	9.118	14.073	11.187	2.765
261	1532.1	721.2	411.3	9.321	15.235	13.070	2.124
291	1878.3	440.0	326.1	12.454	15.077	12.284	4.269
Average	1673.9	551.1	362.9	13.19	15.94	13.25	3.157
Std. dev.	160.71	112.28	37.36	4.61	1.72	1.72	0.792
CV	9.60	20.38	10.29	34.94	10.79	13.02	25.077

Note: CV = coefficient of variation (percent standard deviation).

Table 26. Elastic stiffnesses (E_t or G_t) 33-lb liner.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
61	1958.7	782.9	436.2	16.815	20.120	15.934	2.502
102	2100.1	553.9	422.8	13.612	21.831	15.869	3.792
111	2370.4	838.2	523.4	18.506	26.111	21.228	2.828
142	1968.6	611.0	429.7	15.690	24.365	21.840	3.222
151	2148.1	717.9	486.6	15.535	26.333	21.306	2.992
161	2188.5	787.7	491.5	15.064	26.710	21.576	2.778
171	2096.5	790.9	468.3	12.670	20.437	17.217	2.651
181	2073.1	916.4	492.2	19.494	29.984	26.955	2.262
192	2095.3	713.7	437.9	13.307	21.112	17.205	2.936
201	2210.2	707.5	447.3	10.321	16.968	14.130	3.124
214	2899.4	813.0	514.1	21.498	27.156	21.828	3.566
242	1635.0	1056.0	478.1	11.289	17.404	17.183	1.548
262	2004.1	724.6	445.7	11.298	19.388	16.275	2.766
292	2008.7	710.5	433.9	12.906	18.592	15.950	2.827
321	2376.7	860.6	508.2	8.257	14.909	12.855	2.762
Average	2142.2	772.3	467.7	14.42	22.09	18.49	2.837
Std. dev.	274.65	121.35	33.73	3.62	4.44	3.77	0.525
CV	12.82	15.71	7.21	25.08	20.08	20.41	18.508

Note: CV = coefficient of variation (percent standard deviation).

Table 27. Elastic stiffnesses (Et or Gt) 42-lb liner.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
62	2840.1	1077.9	639.5	21.188	31.720	27.033	2.635
81	2791.1	962.3	590.4	15.612	28.591	23.595	2.900
103	2671.3	859.1	587.4	25.292	31.813	24.195	3.109
112	2800.7	837.1	561.9	18.499	29.991	23.624	3.346
143	2233.3	938.8	546.1	32.281	40.303	38.808	2.379
152	2423.0	857.9	568.9	12.448	26.535	21.391	2.824
162	3077.9	1050.9	618.7	13.212	27.260	22.806	2.929
172	2660.6	776.5	518.0	11.552	27.311	21.830	3.427
182	2467.4	971.1	556.3	12.134	26.176	20.533	2.541
193	3245.8	954.3	591.6	20.168	33.258	26.911	3.401
202	2775.5	869.0	563.0	9.933	22.921	18.532	3.194
212	2996.4	713.9	535.4	20.829	29.880	23.370	4.197
243	2549.3	1046.4	564.9	16.554	27.292	22.505	2.436
251	3101.9	681.6	550.6	13.298	26.702	20.596	4.551
263	2669.5	988.3	586.0	13.489	24.258	19.193	2.701
273	2473.7	1385.4	672.8	16.875	24.028	23.227	1.786
281	2895.5	907.3	571.8	16.215	24.389	20.136	3.191
293	2604.3	1031.1	588.1	12.039	21.896	18.282	2.526
311	2707.8	811.9	508.1	13.601	26.353	20.798	3.335
322	3015.2	963.3	581.3	9.944	20.425	17.530	3.130
Average	2750.0	934.2	575.0	16.26	27.56	22.74	3.027
Std. dev.	257.17	152.91	38.52	5.57	4.51	4.58	0.623
CV	9.35	16.37	6.70	34.24	16.36	20.13	20.598

Note: CV = coefficient of variation (percent standard deviation).

Table 28. Elastic stiffnesses (E_t or G_t) 69-lb liner.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
63	4161.7	1630.8	934.5	32.021	58.560	46.846	2.552
82	3547.2	1519.6	904.0	20.393	43.076	34.965	2.334
113	3743.0	1524.0	891.8	25.492	53.476	43.484	2.456
144	3214.2	1497.9	801.2	30.815	53.712	46.553	2.146
173	3463.6	1607.1	874.8	22.231	50.264	42.169	2.155
183	4214.0	1209.8	835.4	18.258	42.199	33.669	3.483
194	3578.5	1624.0	866.6	22.806	43.412	36.073	2.204
203	4108.4	1311.5	848.6	13.542	35.974	27.449	3.133
213	4030.6	1517.0	897.4	26.597	54.657	43.704	2.657
225	4595.9	747.2	687.5	28.352	60.978	45.165	6.151
244	3327.6	1615.1	904.4	17.757	37.335	32.891	2.060
252	4131.5	1402.0	854.8	17.612	45.340	34.203	2.947
274	3388.8	1779.1	965.6	25.110	45.958	40.073	1.905
282	3612.5	1962.2	1016.7	27.137	44.140	43.023	1.841
294	4204.2	1799.8	971.6	23.068	43.414	37.027	2.336
312	3821.7	1445.7	865.4	23.027	44.427	35.054	2.643
Average	3821.5	1512.0	882.5	23.39	47.31	38.90	2.688
Std. dev.	395.84	275.26	75.80	5.07	7.22	5.73	1.025
CV	10.36	18.20	8.59	21.67	15.26	14.73	38.128

Note: CV = coefficient of variation (percent standard deviation).

Table 29. Elastic stiffnesses (Et or Gt) 26-lb medium.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
11	1210.9	488.0	286.8	17.935	19.820	16.304	2.481
12	1184.1	511.1	278.1	18.025	17.932	14.853	2.317
21	1479.9	409.9	287.6	17.829	16.715	14.835	3.610
31	1306.5	530.0	296.0	20.013	16.949	14.004	2.465
41	1525.9	463.5	301.3	18.120	14.583	12.879	3.292
42	1437.1	454.2	335.5	17.544	14.451	12.686	3.164
51	1282.4	545.4	306.4	19.438	15.639	12.386	2.351
71	1055.5	492.1	261.7	22.471	13.933	14.157	2.145
91	1366.1	387.0	275.7	18.616	19.712	13.954	3.530
121	1112.0	461.6	275.7	22.659	16.761	13.761	2.409
122	1128.3	530.9	298.2	21.322	15.523	13.230	2.125
123	1203.7	506.4	288.7	22.749	18.224	16.306	2.377
124	1171.1	482.1	276.0	22.048	14.793	14.596	2.429
125	1145.5	511.1	282.2	22.385	19.517	15.694	2.241
126	1235.6	477.5	283.9	23.115	18.001	17.034	2.587
127	1137.7	485.9	273.9	22.840	16.205	14.457	2.341
131	1205.7	671.2	339.1	19.684	18.752	17.252	1.796
184	1579.7	468.6	323.6	15.628	17.227	15.153	3.371
191	1854.8	506.4	343.7	15.796	16.486	13.540	3.663
211	1240.4	637.9	316.6	20.762	14.243	12.435	1.944
221	1573.9	386.9	294.2	15.487	18.294	15.074	4.068
231	1329.7	465.1	288.8	21.101	14.914	13.810	2.859
271	1441.3	678.6	353.3	20.473	13.640	13.372	2.124
295	1410.3	583.6	322.4	17.420	16.674	13.361	2.417
301	1105.5	482.7	260.6	17.707	18.449	15.491	2.290
302	1238.0	528.3	285.5	18.492	20.202	16.400	2.344
Average	1306.2	505.6	297.5	19.60	16.83	14.50	2.644
Std. dev.	187.65	73.15	25.38	2.40	1.96	1.40	0.600
CV	14.37	14.47	8.53	12.25	11.67	9.65	22.686

Note: CV = coefficient of variation (percent standard deviation).

Table 30. Elastic stiffnesses (E_t or G_t) 33 to 36-lb medium.
Stiffness units = kN/m.

Lot No.	E_{xt}	E_{yt}	G_{xyt}	E_{zt}	G_{xzt}	G_{yzt}	R
13	1562.2	630.1	378.8	27.328	30.740	27.388	2.479
22	1884.9	574.8	395.4	26.046	26.123	23.325	3.279
32	1488.3	645.2	354.1	23.985	24.841	22.102	2.307
52	1571.5	704.1	359.8	29.707	25.026	23.194	2.232
72	1250.4	698.1	336.3	31.230	23.001	18.618	1.791
92	1574.3	602.6	359.1	24.761	26.418	21.715	2.613
128	1384.5	649.0	381.3	27.743	22.693	21.485	2.133
132	1668.5	750.0	408.9	26.038	31.473	29.521	2.225
185	2227.4	722.0	442.1	23.141	28.157	24.418	3.085
232	1546.7	703.1	446.9	35.902	23.387	21.696	2.200
303	1450.2	743.8	371.9	27.683	29.129	27.638	1.950
53	1791.2	835.1	427.2	33.846	25.479	24.030	2.145
233	1612.6	775.8	410.2	41.808	26.574	24.701	2.079
Average	1616.4	694.9	390.2	29.17	26.39	23.83	2.347
Std. dev.	245.30	73.17	35.00	5.33	2.81	2.97	0.426
CV	15.18	10.53	8.97	18.28	10.65	12.47	18.151

Note: CV = coefficient of variation (percent standard deviation).

Table 31. Elastic stiffnesses (Et or Gt) 40 to 42-lb medium.
Stiffness units = kN/m.

Lot No.	Ext	Eyt	Gxyt	Ezt	Gxzt	Gyzt	R
54	1996.0	977.5	479.5	39.038	36.808	30.268	2.042
73	1461.9	782.1	393.4	34.714	32.364	25.242	1.869
93	1824.9	585.3	430.8	37.184	41.329	34.356	3.118
129	1668.6	874.7	434.9	36.311	32.607	31.538	1.908
222	2122.2	829.1	496.3	29.139	36.602	31.011	2.560
223	2300.9	874.2	509.4	32.830	38.412	32.990	2.632
272	2328.5	915.8	502.4	29.002	32.384	26.838	2.543
304	1507.2	841.8	415.7	28.352	34.068	30.208	1.791
186	2437.6	1004.6	560.7	27.318	35.147	33.416	2.426
Average	1960.9	853.9	469.2	32.65	35.52	30.65	2.321
Std. dev.	364.69	122.85	53.83	4.35	3.07	3.00	0.445
CV	18.60	14.39	11.47	13.33	8.65	9.78	19.167

Note: CV = coefficient of variation (percent standard deviation).

Table 32. Elastic stiffnesses (Et or Gt) 52-lb medium.
Stiffness units = kN/m.

Lot No.	Ext	Eyt	Gxyt	Ezt	Gxzt	Gyzt	R
224	2983.4	1283.8	707.0	42.833	62.553	50.626	2.324
Average	2983.4	1283.8	707.0	42.83	62.55	50.63	2.324
Std. dev.	0.00	0.00	0.00	0.00	0.00	0.00	0.000
CV	0.00	0.00	0.00	0.00	0.00	0.00	0.000

Note: CV = coefficient of variation (percent standard deviation).

Table 33. ECT - liners combined with standard medium.

Lot No.	Basis Weight ^a	ECT, lb/inch	Lot No.	Basis Weight ^a	ECT, lb/inch
101	26.3	34.0	63	70.2	70.2
141	28.9	33.8	82	68.2	56.7
241	26.7	32.2	113	68.3	62.0
261	26.6	34.4	144	68.6	60.9
			173	67.8	63.7
61	33.2	40.9	183	70.5	55.2
102	33.3	37.0	194	70.7	58.9
111	34.5	44.6	203	68.4	56.7
142	34.9	38.0	213	68.9	64.7
151	32.9	39.4	244	70.2	56.6
161	33.3	41.3	252	67.8	62.8
171	33.3	37.8	274	71.6	72.4
181	34.0	40.3	294	69.6	65.3
192	34.8	39.6	312	67.9	53.0
201	33.9	39.8			
214	35.1	44.6			
242	32.8	40.2			
262	33.6	35.6			
292	33.7	41.6			
321	34.2	37.5			
62	43.7	48.8			
81	41.6	43.7			
103	42.8	46.9			
112	42.1	45.6			
143	41.8	47.6			
162	43.8	42.8			
172	42.2	41.1			
182	41.7	43.5			
193	43.9	48.3			
202	41.6	42.6			
243	42.5	46.6			
251	42.9	41.5			
263	42.5	42.4			
311	40.1	43.1			

^aBasis weight of liner, lb/1000 ft².

Table 34. ECT and flat crush - mediums combined with standard liner.

Lot No.	Basis Weight ^a	ECT, lb/inch	Flat Crush, psi	Lot No.	Basis Weight ^a	ECT, lb/inch	Flat Crush, psi
12	26.4	43.7	35.6	13	35.0	45.9	37.9
21	26.6	42.2	35.8	22	33.4	44.4	43.5
41	26.8	42.6	36.4	52	33.2	46.7	43.2
42	26.5	41.9	38.6	72	33.0	47.6	43.0
51	26.6	45.4	32.6	128	33.0	48.0	37.5
71	26.4	43.8	35.0	132	33.0	48.7	45.1
91	26.9	41.1	35.0	185	34.2	47.3	40.7
121	26.3	44.7	45.0	232	33.0	48.4	55.7
122	26.2	45.2	31.8	303	33.5	49.5	45.7
123	26.4	42.7	32.8				
125	26.3	42.7	34.1	53	37.0	48.8	39.1
126	26.4	43.1	33.9	233	35.5	50.9	59.5
127	26.3	43.2	32.2				
184	26.4	44.6	44.7	54	41.2	50.6	43.6
191	26.5	43.0	36.9	73	39.5	49.8	41.8
221	26.3	40.4	35.8	93	40.4	47.9	49.7
231	25.9	41.3	32.2	129	39.4	52.1	49.2
301	25.0	42.0	32.8	222	39.5	49.3	44.0
302	26.6	42.7	34.2	223	42.5	51.8	39.3
				186	43.7	52.0	38.3
				224	54.2	55.1	45.3

^aBasis weight of medium, lb/1000 ft².

APPENDIX II
TEST PROCEDURES

All materials were preconditioned at less than 35%, 23°C and conditioned at 50 ± 2% RH, 23°C prior to test. The tests and procedures employed are shown in Table 35.

Table 35. Test procedures.

Test	No. of Tests	Test Procedure
1. Basis weight	5	T410
2. Caliper, TAPPI	20	T411
3. Caliper, IPC	5	IPC ^a
4. Ring crush, MD	10	T818
CD	10	T818
5. Taber stiffness MD	5	T489
CD	5	T489
6. STFI compressive strength, MD	20	--b
CD	20	--b
7. Concora (medium only)	10	T809
8. Bursting strength (liners only)	10	T807
9. In-plane elastic stiffnesses	5	IPC ^c
10. ZD elastic stiffness	5	IPC ^c
12. Out-of-plane shear stiffnesses	3	IPC ^c

^aIPC compressible platen thickness gage (see Hardacker, K.W., IPC Technical Paper Series No. 138. Jan., 1984).

^bModel 53M STFI compression tester, according to manufacturer's instructions.

^cInstitute procedures for ultrasonic stiffness determinations.

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