THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

A STUDY OF THE EFFECT OF FIBER AND PROCESS VARIABLES ON THE MECHANICAL PROPERTIES OF THE COMPONENTS OF COMBINED BOARD

PART I. EFFECT OF BASIS WEIGHT AND DEGREE OF REFINING ON THE PROPERTIES OF KRAFT HANDSHEETS

✓Project 1108-4

A

Preliminary Report

to the

TECHNICAL COMMITTEE

FOURDRINIER KRAFT BOARD INSTITUTE, INC.

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SUMMARY

A study of broad scope is in progress to determine the effect of fiber and processing variables on the mechanical properties of the components of combined board which are important to box compression performance. These properties include modified ring compression, modulus of elasticity, and Taber stiffness.

The initial phase of this study is described in this report. It was found that the mechanical properties of kraft handsheets made from a given furnish vary linearly (or are constant) with basis weight in the range of 14 to 27 lb./1000 sq. ft. (An exception is Taber stiffness, although its behavior is predictable in terms of modulus of elasticity and caliper.) This result justifies the succeeding phase of research, which involves laminating a given number of handsheets into sheets of commercially significant weights. This second phase should permit studying the effect of basis weight independent of formation effects.

The initial phase of study also included a range of degree of refining. It was found that the mechanical properties (with the exception of Taber stiffness) increased markedly with increase in refining in the range of 800 to 600 cc. freeness (Canadian standard). From 600 to 500 cc. freeness, there was little further change in the properties. Taber stiffness decreased with increased refining; this trend is explainable in terms of the changes brought about in modulus of elasticity and caliper.

Several interrelationships between the mechanical properties are examined, which are of theoretical and practical importance.

INTRODUCTION

Top-to-bottom box compression strength has been shown to depend primarily on two properties of combined board, namely, cross-direction edgewise compression strength and flexural stiffness in each principal direction (1). Each of these combined board properties is related to certain material properties of the components and the geometry of the combined board. Recent studies have indicated that the combined board edgewise compression strength depends upon (a) edgewise compression strength (modified ring compression) of the individual liners and medium, (b) flexural stiffness (Taber) of the liners and medium [though less importantly than on (a)], and (c) flute pitch and draw factor (2).

Flexural stiffness of the combined board depends upon (a) modulus of elasticity of the components, (b) caliper of the components, (c) caliper of combined board, and (d) flute shape (3).

Considering both types of combined board properties described above, it may be seen that the component properties which are of importance to box compression are:

(a) edgewise compression strength

(b) modulus of elasticity

(c) Taber stiffness

(d) caliper

A research program of broad scope is in progress to determine the effect of fiber and processing variables on these component properties. The knowledge and data acquired from this study can be expected to have far-reaching consequences to the selection of raw materials, processing, and the manufacture and use of linerboard and corrugating medium.

A portion of this research program is concerned with a fundamental study of the mechanisms involved in the edgewise compression performance of components. This is perhaps the least well-understood property of the several mentioned above. Because of its dominant role in box compression, an understanding of the mechanism of failure is of paramount importance. This phase of the study seeks to determine the role of bonding and fiber properties in edgewise compression performance. Work now in progress is directed to studying bond behavior in a sheet under edgewise compressive stress through the use of optical measurements.

A second portion of the research program is directed to a study of fiber and process variables. The results can be expected to find direct application in present-day manufacturing operations. It is planned that this portion will include studies in such areas as fiber species, refiner variables, beater additives, drying tensions, wet and dry pressing, surface bonding agents, varying secondary stock treatment, etc.

A study of such scope and diversity should be built upon a strong foundation of basic information, and this in turn must begin with rather rudimentary considerations. The present report deals with an initial phase of the broader study — a phase directed to quite elementary, though nonetheless important, characteristics of kraft handsheets.

In order to study fiber and processing variables on a laboratory scale, it is necessary to establish a technique of making handsheets in weights which are of commercial significance (the "standard" handsheet weighs only 13-14 lb./1000 sq. ft.). Care must be exercised when going to heavier weight handsheets that the effects under study are not confused by the worsening of formation which generally accompanies an increase in basis weight. A better technique is wet-lamination of several handsheets of moderate weight. Thus, a 42-lb. sheet may be built up from three 14-lb. handsheets, and a 69-lb. sheet from three 23-lb. handsheets. Numerous other combinations are possible, of course.

This lamination technique requires that formation effects be constant when changing from one weight of single-ply handsheet to another, for example, from 14 to 23 lb./1000 sq. ft. A way of determining whether or not formation effects are constant is to study the relationship between modified ring compression (or other mechanical properties) and basis weight over the range of handsheet weights which will be used in laminating. Thus, if ring compression is proportional to basis weight in the range of, say, 14 to 27 lb./1000 sq. ft., handsheets having basis weights within this range can be laminated together without introducing significant changes in formation.

The present report is concerned largely with this latter aspect; namely, the relationship between the component properties cited at the outset (ring compression, Taber, etc.) and basis weight of kraft handsheets in the range of 14 to 27 lb./1000 sq. ft. The experimentation was arranged to include four degrees of refining, thereby giving valuable insight into the effect of refining on the "engineering" properties of components. Moreover, a number of interrelationships between the engineering properties are examined, which have both theoretical and practical significance.

TEST PROCEDURE

A sample of 100% unbleached southern pine kraft pulp was refined in a 1-1/2 lb. Valley beater to four freeness levels: nominally 800, 700, 600, and 500 cc. (Canadian standard). Ten British handsheets were made in each of four nominal basis weights – 14, 19, 23, and 27 lb./1000 sq. ft. – at each freeness level according to TAPPI method T 205 m-58.

After standard conditioning, the following tests were performed on each handsheet:

(a) Basis weight

(b) Modified ring compression (2 by 1/2 inch, H & D test machine)

(c) Taber stiffness (Taber V5 test instrument)

(d) Instron tension (5-in. span, 1-in. width, strain rate 0.1 in./in./min.)

(e) z-direction tension (See discussion below)

(f) Caliper (3 determinations on each Taber specimen and one determination on each Instron tension specimen)

Modulus of elasticity, E, and extensional stiffness, Et, were determined from the slope of the tension load-elongation curve in the elastic range.

The z-direction tension test evaluates the transverse tensile strength of the sheet. The surfaces of a circular specimen of one-inch diameter are adhered to two cylindrical blocks with epoxy resin. After curing, the blocks are pulled apart in a tensile testing machine; resulting in a cleavage of the specimen along an interior plane parallel to the sheet surfaces. The strength at rupture may be taken as a measure of the strength of the bonds between fibers of the sheet, although at this stage of its development at The Institute of Paper Chemistry, it has not been determined that the test measures solely bonding strength.

DISCUSSION OF RESULTS

RELATIONSHIPS BETWEEN COMPONENT PROPERTIES, BASIS WEIGHT, AND DEGREE OF REFINING

The controlled variables in this experiment were degree of refining and basis weight. One set of ten handsheets was made at each of four levels of refining and basis weight, for a total of 16 combinations. The freeness (cc., Canadian standard) and basis weight of each condition are shown in Table I. Each entry in this table (as in all succeeding tables except those for caliper and density) is an average of ten determinations — one determination per handsheet.

TABLE I

BASIS WEIGHT AND FREENESS FOR EACH TEST CONDITION

Freeness, cc.	Basis Weight, lb./1000 sq. ft.			
780	14.0	18.7	23.0	25.7
705	14.1	18.8	24.0	27.2
590	13.9	18.4	23.0	26.8
480	14.0	18.2	22.9	27.8
Av.	14.0	18.5	23.2	26.9

The average caliper of the handsheet for each condition is shown in Table II. It may be seen that caliper decreased with increased degree of refining (decrease in freeness) as would be expected. There was little change in caliper, however, between 590 and 480-cc. freeness. Caliper increased with increase in basis weight, as would be anticipated.

The apparent density of the handsheets is shown in Table III. Apparent density was calculated by dividing basis weight by caliper. It may be seen that the density increased markedly with increase in refining (decreasing freeness) as

TABLE II

CALIPER OF HANDSHEETS

CALIPER, 10^{-3} in.

Average Basis Weight Level, lb./1000 sq. ft.

Freeness, cc.	14	19	23	27	Av.
780	6.1	8.3	10.0	11.1	8.9
705	5.3	6.8	8.5	9.7	7.6
590	4.8	6.0	7.2	8.2	6.6
480	4.8	5.9	7.0	8.3	6.5
Av.	5.2	6.8	8.2	9.3	7.4

TABLE III

APPARENT DENSITY OF HANDSHEETS

$$\text{APPARENT DENSITY} = \frac{\text{Actual Basis Weight}}{\text{Caliper}},\ 10^{3}\ \frac{\text{lb.}}{\text{in.(1000 sq. ft.)}}$$

Average Basis Weight Level, lb./1000 sq. ft.

Freeness, cc.	14	19	23	27	Av.
780	2.30	2.25	2.30	2.32	2.29
705	2.66	2.76	2.82	2.80	2.76
590	2.90	3.07	3.19	3.27	3.11
480	2.92	3.08	3.27	3.35	3.16
Av.	2.70	2.79	2.90	2.94	2.83

would be expected because of the decrease in caliper associated with the increased bonding. There was a modest increase in density with increase in basis weight at the higher levels of refining. Possibly, this trend is attributable to increased retention of fines as the thickness of the sheet increased.

The modified ring compression strength of the handsheets is shown in Table IV. A graph of the relationship between modified ring and basis weight at each level of refining is given in Fig. 1. The lines in this and succeeding graphs were fitted visually. It may be seen that, within each freeness level, modified ring strength increased linearly with basis weight.

However, it may be noted that modified ring compression was not directly proportional to basis weight; extrapolation of the lines to zero basis weight indicates that they do not pass through the origin of the graph. Thus, doubling the basis weight of the handsheet more than doubled the ring compression strength. For example, at 480 cc. freeness, the modified ring strength of the 14-lb. sheet was about 7 lb./in. and the strength of the 28-lb. sheet was about 17 lb./in. Similar, though less severe, disparities occur at the other levels of freeness.

Several possible reasons may be suggested for the observed lack of proportionality between modified ring compression and basis weight. One is that slight buckling of the ring specimen may have occurred in the lighter weight, lower caliper sheets, resulting in a counterclockwise rotation of each line away from the origin. In this regard, it may be mentioned that the modified ring test was used in this experiment on considerably lower weight sheets than the test method was developed for.

On the other hand, the nonproportionality between modified ring compression and basis weight may represent a real change in formation of the sheet as

TABLE IV

MODIFIED RING COMPRESSION STRENGTH OF HANDSHEETS

Freeness, cc.	MODIFIED RING COMPRESSION, lb./in. — Average Basis Weight Level, lb./1000 sq.ft.				
	14	19	23	27	Av.
780	4.4	5.5	7.6	7.9	6.4
705	5.8	8.2	11.0	12.6	9.4
590	6.7	9.7	13.0	15.5	11.2
480	7.0	9.8	13.5	16.8	11.8
Av.	6.0	8.3	11.3	13.2	9.7

TABLE V

MODIFIED RING COMPRESSION EFFICIENCY FACTORS

$$\text{MODIFIED RING FACTOR} = \frac{\text{Modified Ring Compression}}{\text{Basis Weight}}, \frac{\text{lb./in.}}{\text{lb./1000 sq.ft.}}$$

Freeness, cc.	Average Basis Weight Level, lb./1000 sq.ft.				
	14	19	23	27	Av.
780	0.314	0.294	0.330	0.307	0.311
705	0.411	0.436	0.458	0.463	0.442
590	0.482	0.527	0.565	0.578	0.538
480	0.500	0.538	0.590	0.604	0.558
Av.	0.427	0.449	0.486	0.488	0.462

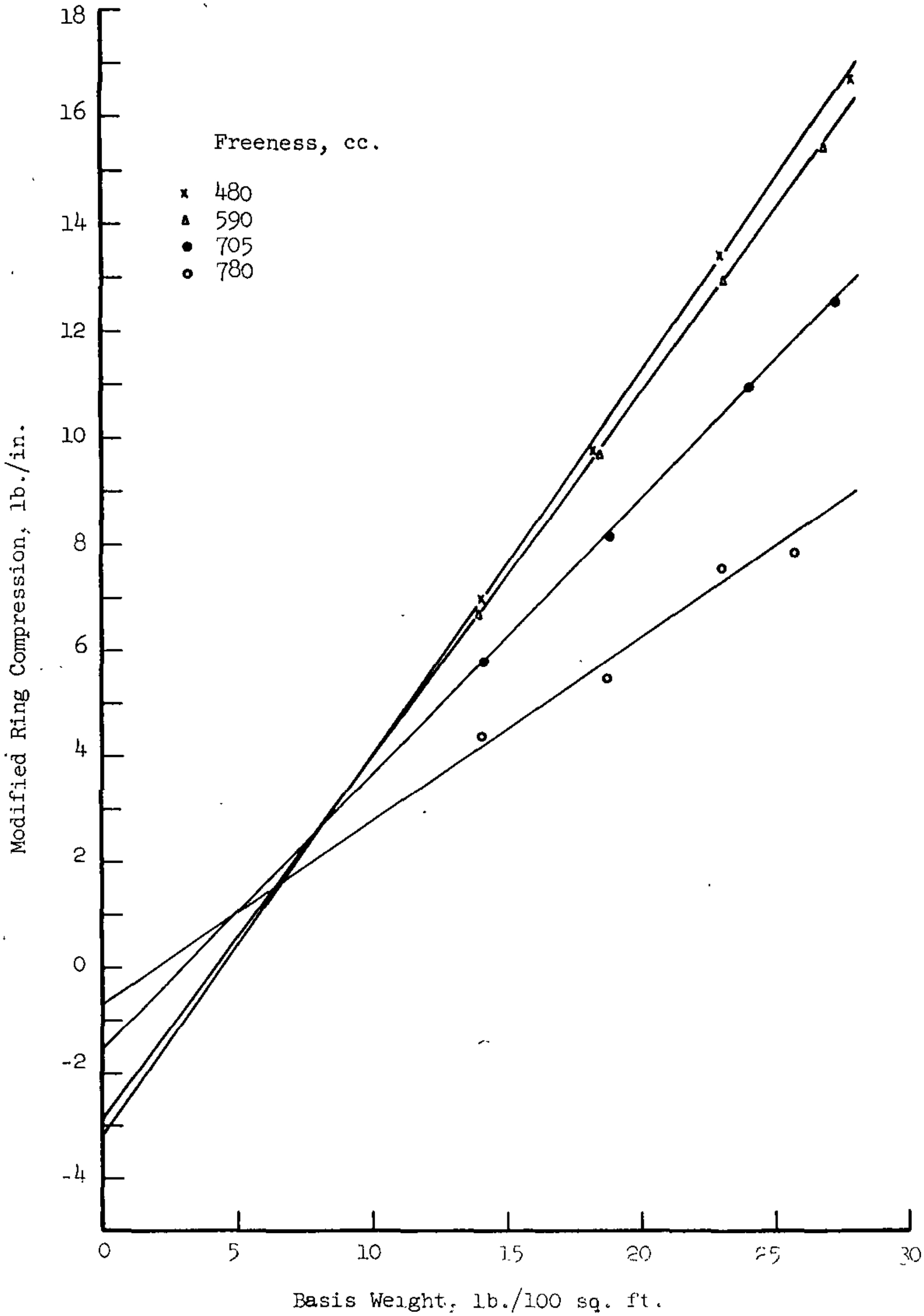

Figure 1. Relationship Between Modified Ring Compression and Basis Weight

basis weight increases. It was noted above that density increased with basis weight, particularly at the higher degrees of refining. A suggested reason was increased retention of fines as the sheet thickness or basis weight increased. It is conceivable that the increased number of fines and the associated "tighter" and better bonded sheet may account for the disproportionate increase in modified ring compression as basis weight increases.

In either event, it is evident that the lack of proportionality between modified ring compression and basis weight requires caution in later phases of this research program when several handsheets are laminated to obtain commercial-weight sheets. It is believed that the effect of nonproportionality can be overcome by using the same number of plies in all laminated constructions. With this technique, the difference in modified ring compression between, say, a 42- and a 69-lb. sheet should be proportional to the difference in basis weight (at a given freeness level). If this proves to be the case, then the effect of basis weight on component strength can be experimentally determined, independently of the worsening formation that usually accompanies increase in basis weight in commercial linerboard.

Table V lists the efficiency factor of each type of handsheet, that is, the modified ring strength per pound of fiber. It may be seen that the efficiency at a given level of basis weight increased with increased refining, as would be anticipated. At a given level of refining there was an apparent increase in the efficiency as the basis weight was increased. For example, at a freeness of 480 cc., the efficiency factor of the 14-lb. sheet was 0.50 lb./in. per pound of fiber, whereas the efficiency of the 27-lb. sheet was 0.60 - a 20% increase. This trend is a direct result of the lack of proportionality between modified ring compression and basis weight discussed above. The reverse trend is usually experienced in liners of commercial weights because of the worsening of formation as the weight increases.

Although the weight of these handsheets is too low to be of commercial significance, it may be of interest to note that calculations based on Fig. 1 indicate that a one-pound increase in basis weight accounted for 0.35 to 0.7 lb./in. increase in modified ring compression. The more highly refined stock gave the larger increase in compression per pound/M ft.^{2} of fiber, as would be anticipated.

Figure 2 is a graph of the relationship between modified ring compression and freeness at given levels of basis weight. Because of the slight variations in the actual basis weight at each nominal basis weight level (see Table I), Figure 2 is a crossplot of Fig. 1 and, in effect, provides a correction for the unavoidable, slight variations in basis weight.

Figure 2 reveals marked increases in modified ring compression in early stages of refining (high freeness), but very minor increases as the freeness is reduced below 600 cc. It may be calculated from these curves that a 50-cc. reduction in freeness accounts for about 0.6 to 2.0 lb./in. increase, on the average, in modified ring compression in the 800 to 600-cc. freeness range — depending on the basis weight level. At low freeness (600 to 500 cc.) there is virtually no further increase in compression, as mentioned above. It is known that regular ring compression goes through a maximum with freeness; however, the level of freeness at which this appears to take place in the present data is much higher than anticipated.

It may be remarked that the levels of modified ring compression exhibited by these handsheets are higher than would be obtained in the cross direction of machine-made linerboard of the same weights, because of the isotropic nature of handsheets.

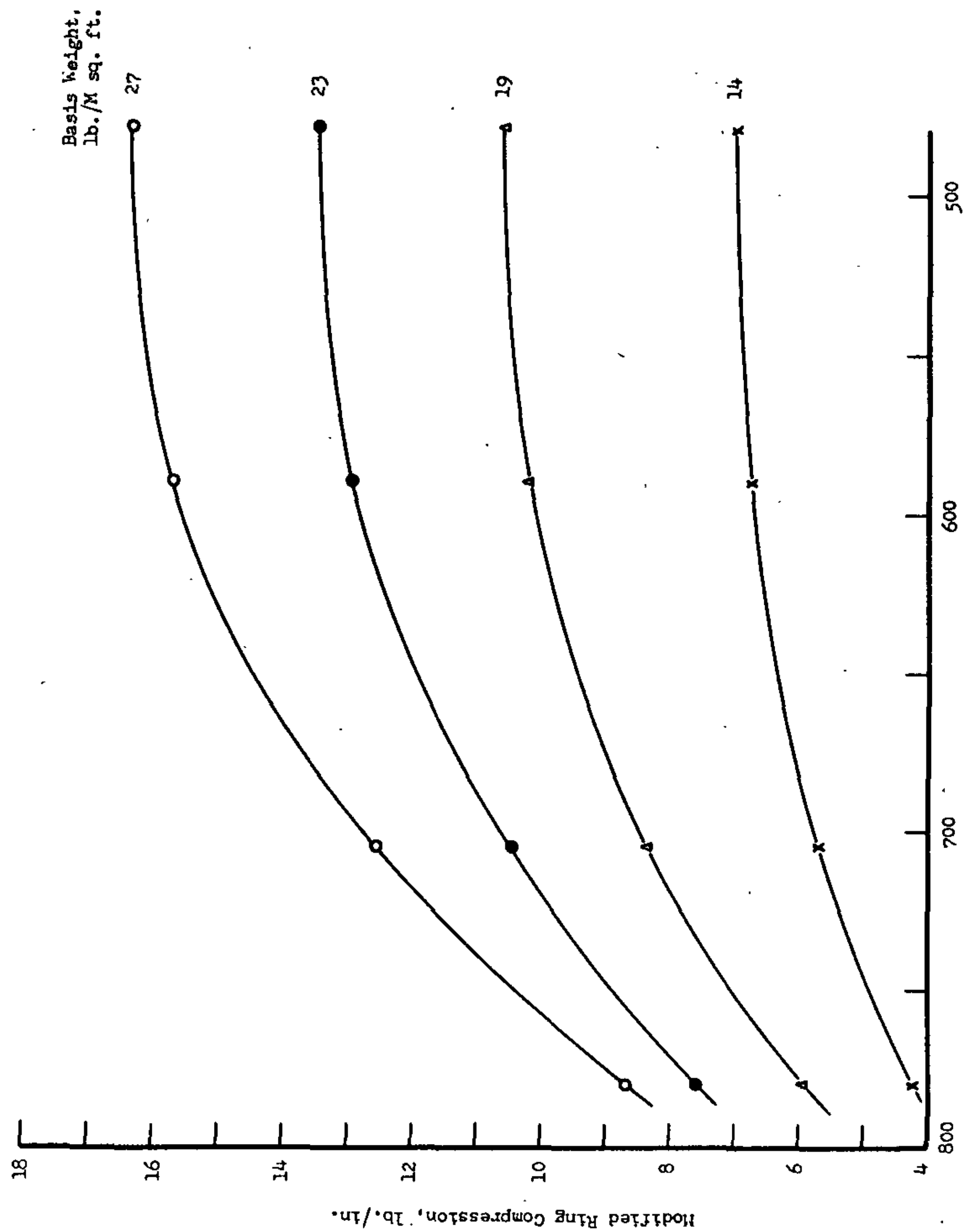

Figure 2. Relationship Between Modified Ring Compression and Degree of Refining

Extensional stiffness, Et, is given directly by the slope of the tension load-elongation curve in the elastic range (except for multiplication by the span of the specimen). This property of liners is of importance to box compression because the flexural stiffness of combined board is, to a first approximation, proportional to extensional stiffness of the liners multiplied by the square of the combined board caliper (3).

The extensional stiffness of the 16 sets of handsheets is listed in Table VI. Figures 3 and 4 show the effect of basis weight and freeness on this mechanical property. It may be seen that Et is linear with basis weight. Inspection of Table V containing the efficiency factors for extensional stiffness (Et divided by basis weight) reveals that the stiffness per pound of fiber is very nearly constant with change in basis weight. This indicates that, unlike modified ring compression, extensional stiffness is very nearly directly proportional to basis weight and, therefore, lamination of handsheets in the 14 to 27-lb. range would not be expected to introduce effects due to changing formation. The observation that increase in basis weight caused disproportionate increase in modified ring compression (a rupture property) and proportional increase in extensional stiffness (an elastic property) possibly may be associated with differing effects of "formation" in the elastic and inelastic regions.

The efficiency factors in Table VII reveal that the extensional stiffness per pound of fiber increased with refining at a given basis weight level, as would be anticipated. This trend is also shown in Fig. 4 where marked increases in Et occur in going from 800 to 600-cc. freeness. Below 600-cc. freeness, however, there was no further increase in extensional stiffness.

TABLE VI

EXTENSIONAL STIFFNESS OF HANDSHEETS

Extensional Stiffness, lb./in.

Average Basis Weight Level, lb./1000 sq.ft.

Freeness, cc.	14	19	23	27	Av.
780	1775	2119	2666	2928	2372
705	2276	2987	3850	4353	3366
590	2669	3600	4430	4934	3908
480	2757	3534	4411	5383	4021
Av.	2369	3060	3839	4400	3417

TABLE VII

EXTENSIONAL STIFFNESS EFFICIENCY FACTORS

$$\text{Extensional Stiffness Factor} = \frac{\text{Extensional Stiffness}}{\text{Basis Weight}}, \quad \frac{\text{lb./in.}}{\text{lb./1000 sq.ft.}}$$

Average Basis Weight Level, lb./1000 sq.ft.

Freeness, cc.	14	19	23	27	Av.
780	127	113	116	114	118
705	161	159	160	160	160
590	192	196	193	184	191
480	197	194	193	194	194
Av.	169	166	166	163	166

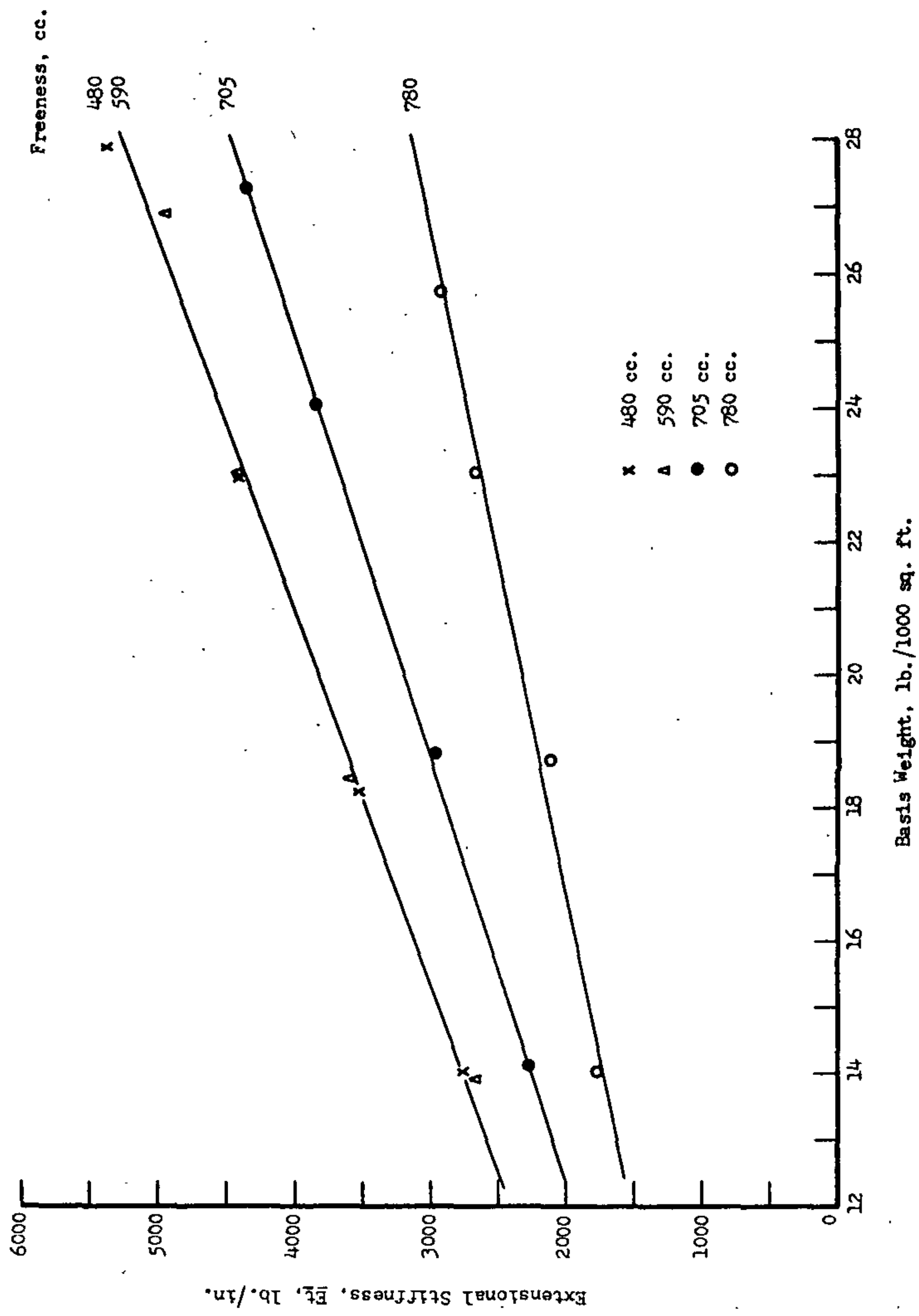

Figure 3. Relationship Between Extensional Stiffness and Basis Weight

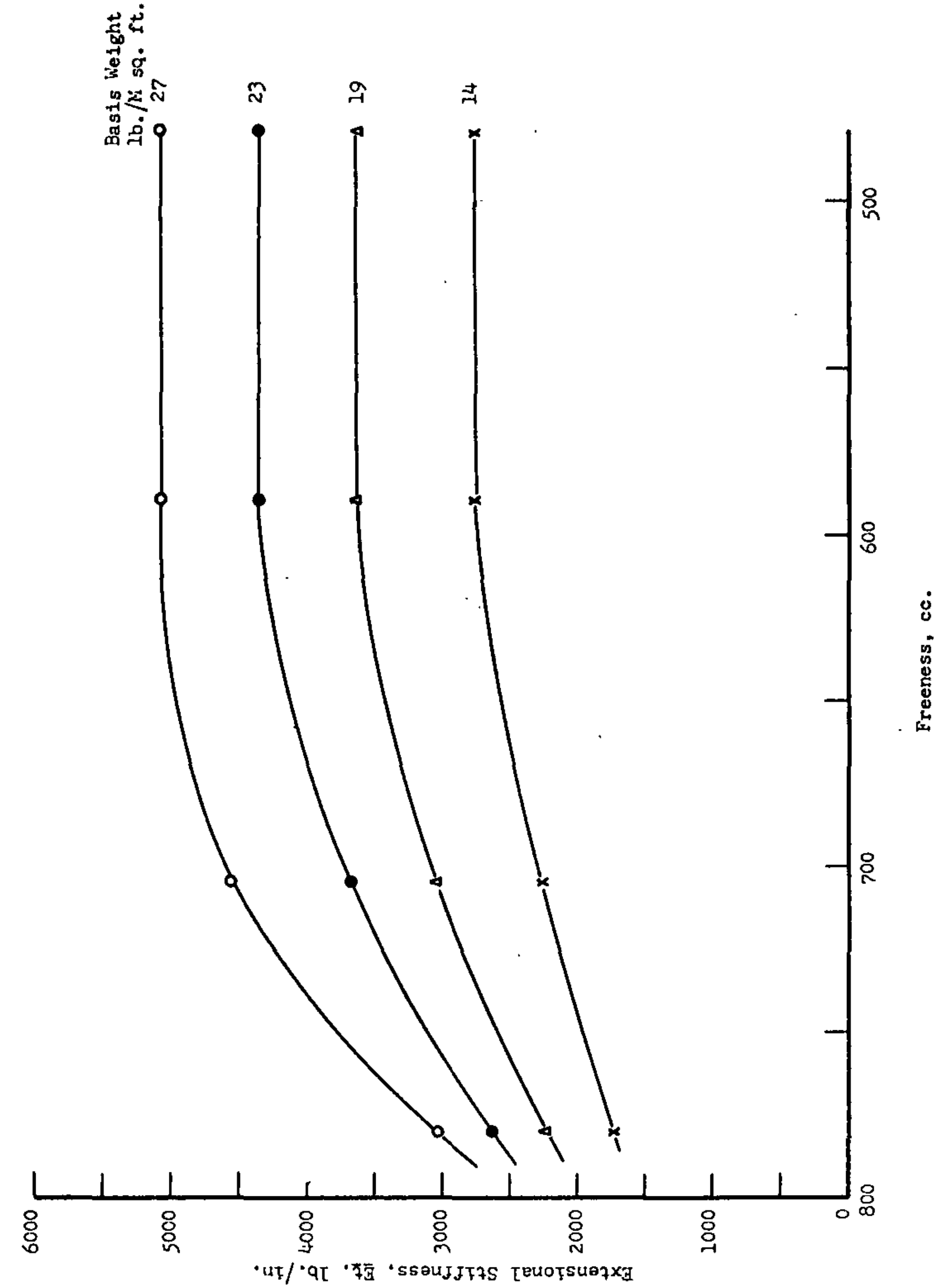

Figure 4. Relationship Between Extensional Stiffness and Degree of Refining

Table VIII and Fig. 5 and 6 show the effect of basis weight and refining on the tension modulus of elasticity, E. There was virtually no change in modulus with increase in basis weight. The fluctuations in E evident in Fig. 5 are probably mainly due to experimental errors, although at 480-cc. freeness there is a slight trend to increased E with increase in basis weight which parallels a similar increase in density as cited above. The observation that E is, in general, independent of basis weight indicates that the aforementioned increase in extensional stiffness, Et, with increase in basis weight is mainly attributable to the associated increase in caliper. Inspection of Fig. 6 reveals that the modulus of elasticity increased markedly with degree of refining; this is a familiar result which is attributed to increased bonding and/or density of the sheet.

Taber stiffness is a measure of the flexural rigidity of a component. Previous work has indicated that it is a factor in the cross-direction edgewise compression strength of combined board (although secondary to modified ring compression), inasmuch as it relates to the stability of the liners between flute tips (2). There are theoretical grounds for expecting that Taber stiffness may be an important factor in end-load compression because failure of the combined board is essentially buckling of individual liners between flute tips in the flaps of the box (4). It should be emphasized that Taber stiffness refers to bending of a liner, whereas extensional stiffness, Et, involves stretching of the liner.

The effect of basis weight and freeness on Taber stiffness is shown in Table IX and Fig. 7 and 8. It may be seen that Taber stiffness increased markedly and nonlinearly with basis weight and, on the other hand, decreased slightly with increase in refining. The reason for these trends may be appreciated by consideration of the more fundamental properties that govern Taber stiffness. Theoretically, the flexural stiffness of a component (whether measured by Taber or other suitable

TABLE VIII

MODULUS OF ELASTICITY OF HANDSHEETS

Freeness, cc.	Modulus of Elasticity, 10^3 lb./sq.in. — Average Basis Weight Level, lb./1000 sq.ft. 14	19	23	27	Av.
780	285	248	261	258	263
705	419	421	440	441	430
590	566	590	596	592	586
480	568	594	620	649	608
Av.	460	463	479	485	472

TABLE IX

TABER STIFFNESS OF HANDSHEETS

Freeness, cc.	Taber Stiffness, units — Average Basis Weight Level, lb./1000 sq.ft. 14	19	23	27	Av.
780	3.2	6.9	11.8	16.1	9.5
705	3.2	6.3	12.5	19.2	10.3
590	2.5	5.1	9.2	15.4	8.0
480	2.4	4.8	8.5	15.8	7.9
Av.	2.8	5.8	10.5	16.6	8.9

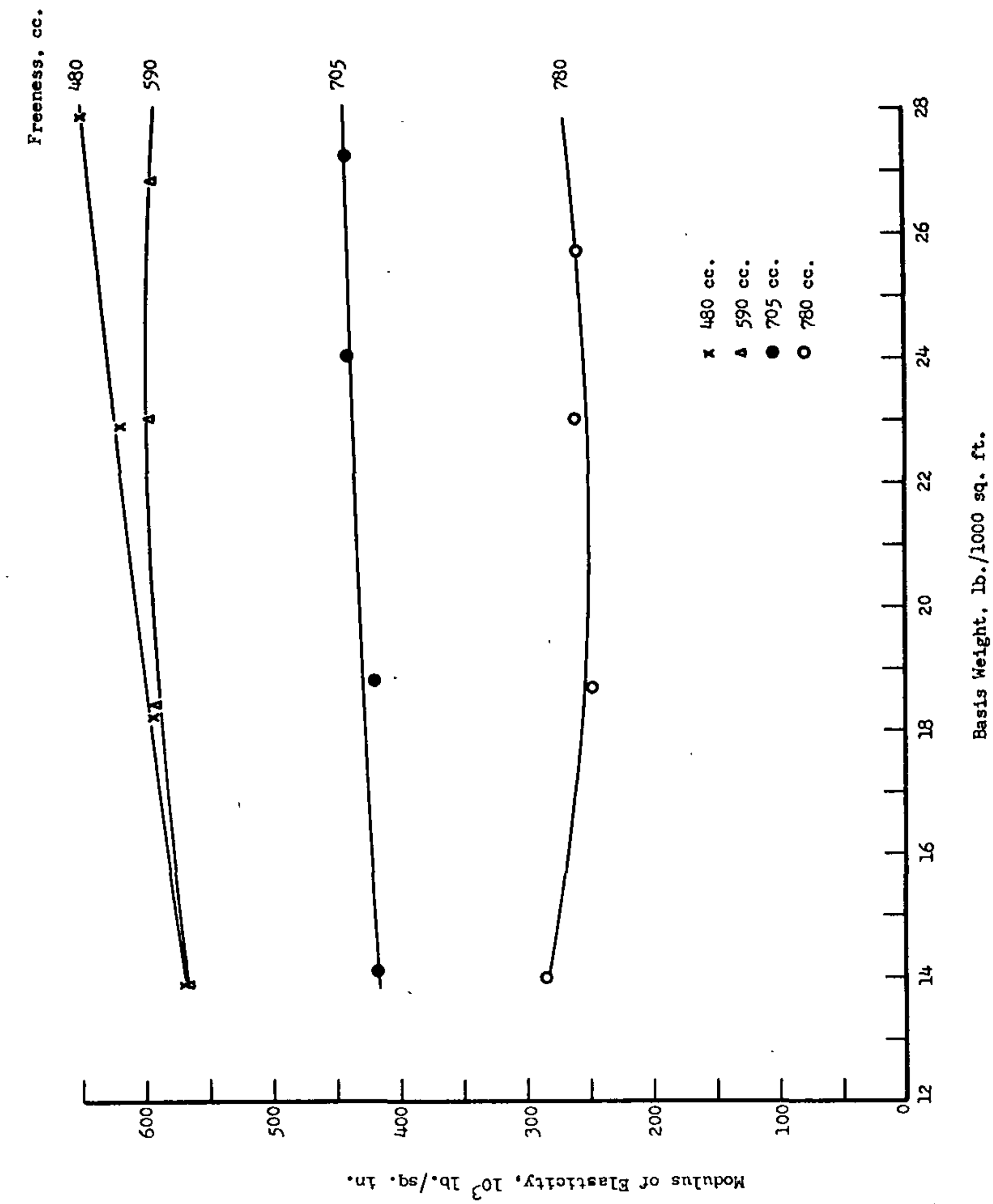

Figure 5. Relationship Between Tension Modulus of Elasticity and Basis Weight

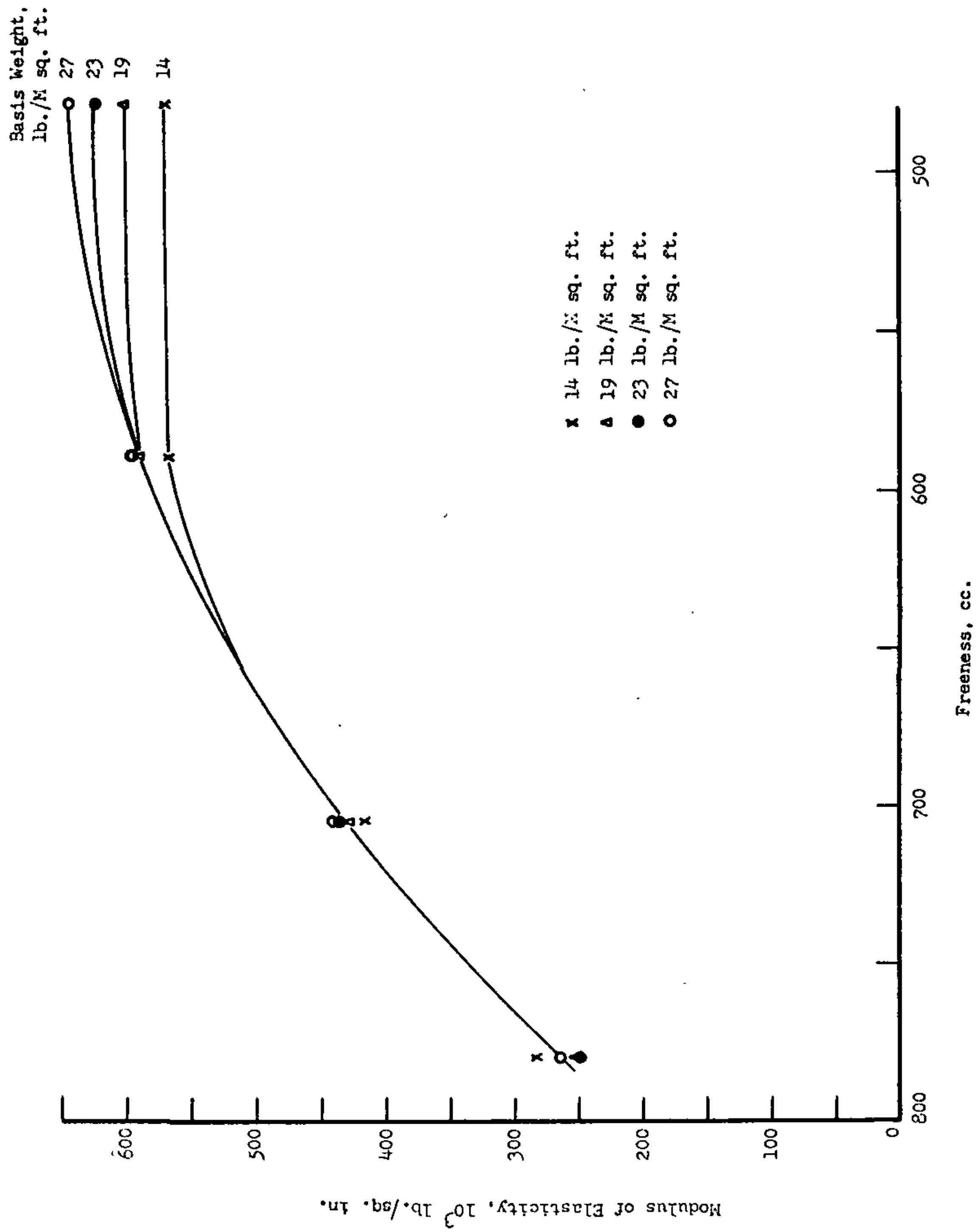

Figure 6. Relationship Between Tension Modulus of Elasticity and Degree of Refining

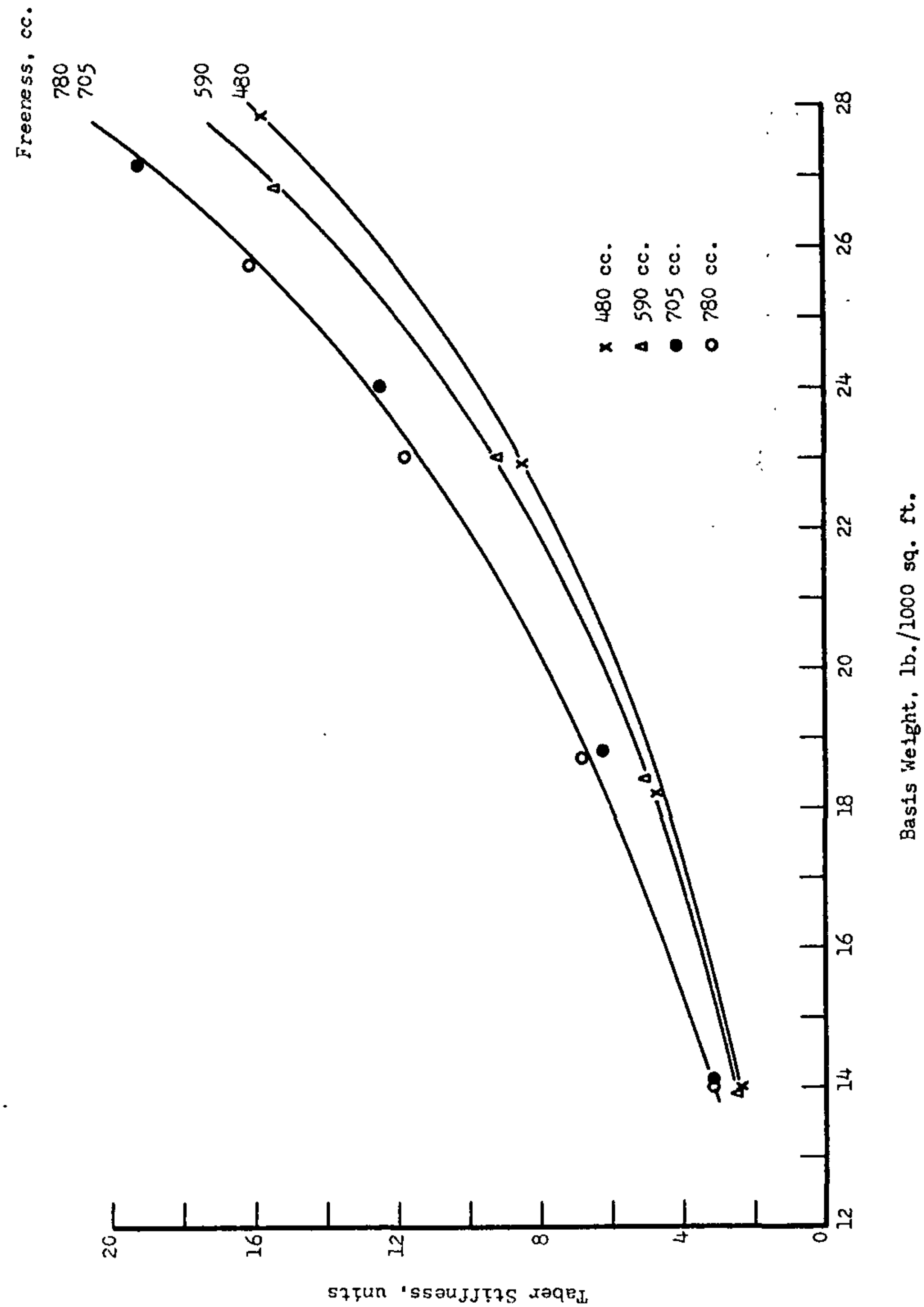

Figure 7. Relationship Between Taber Stiffness and Basis Weight

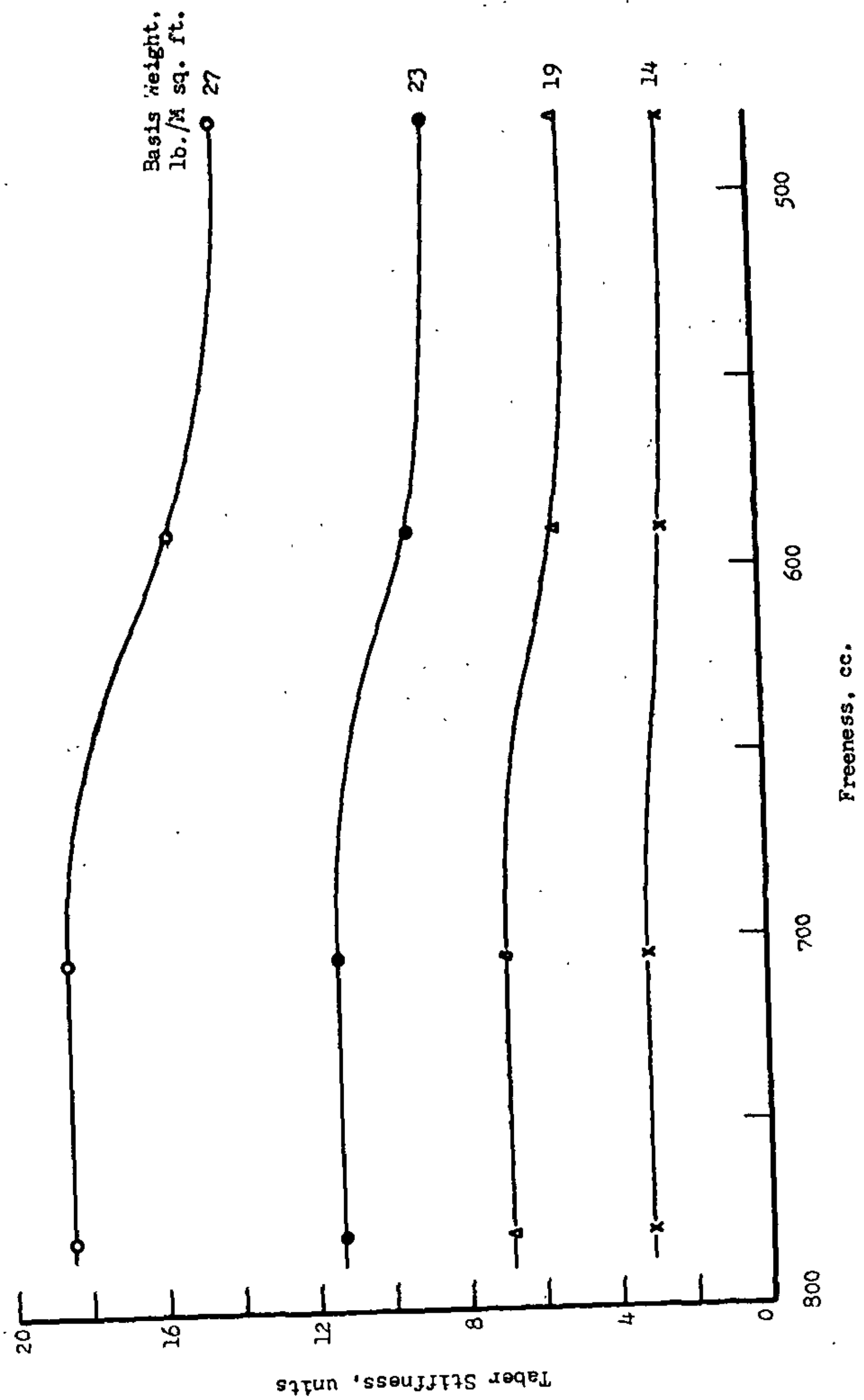

Figure 8. Relationship Between Taber Stiffness and Degree of Refining

flexure test) is proportional to Et^3, where E is modulus of elasticity and t is caliper. That this relationship is indeed valid may be seen in Fig. 9, which shows a linear relationship between Taber stiffness and Et^3 which is virtually independent of basis weight and freeness.

Thus, the highly curvilinear relationship between Taber stiffness and basis weight (Fig. 7) is explainable by the associated increase in caliper which enters as the third power; modulus of elasticity is essentially independent of basis weight, as noted earlier.

Figure 8 reveals a rather intricate relationship between Taber stiffness and degree of refining. In general, Taber stiffness decreased with increase in refining. While refining tends to increase modulus of elasticity, this increase is more than offset by the associated decrease in caliper (entering as the third power) and the net effect is a decrease in Taber stiffness. This result indicates that increases in modified ring compression achieved by increased refining would be at the expense of Taber stiffness. Thus, the increase in combined board edgewise compression (cross direction) may not be as great as the change in modified ring strength would indicate, and there possibly may be a loss in end-load box strength. Further fundamental work in both of these latter areas is necessary before much confidence can be attached to these speculations, but the trends evident in this initial work are believed to warrant further investigation in later phases of this research program.

The observation that Taber stiffness is not linear with basis weight is of no great consequence in so far as the requirements for laminating handsheets are concerned. Taber stiffness is not a fundamental test, in the sense that it is relatable to and predictable from more fundamental tests which are in themselves

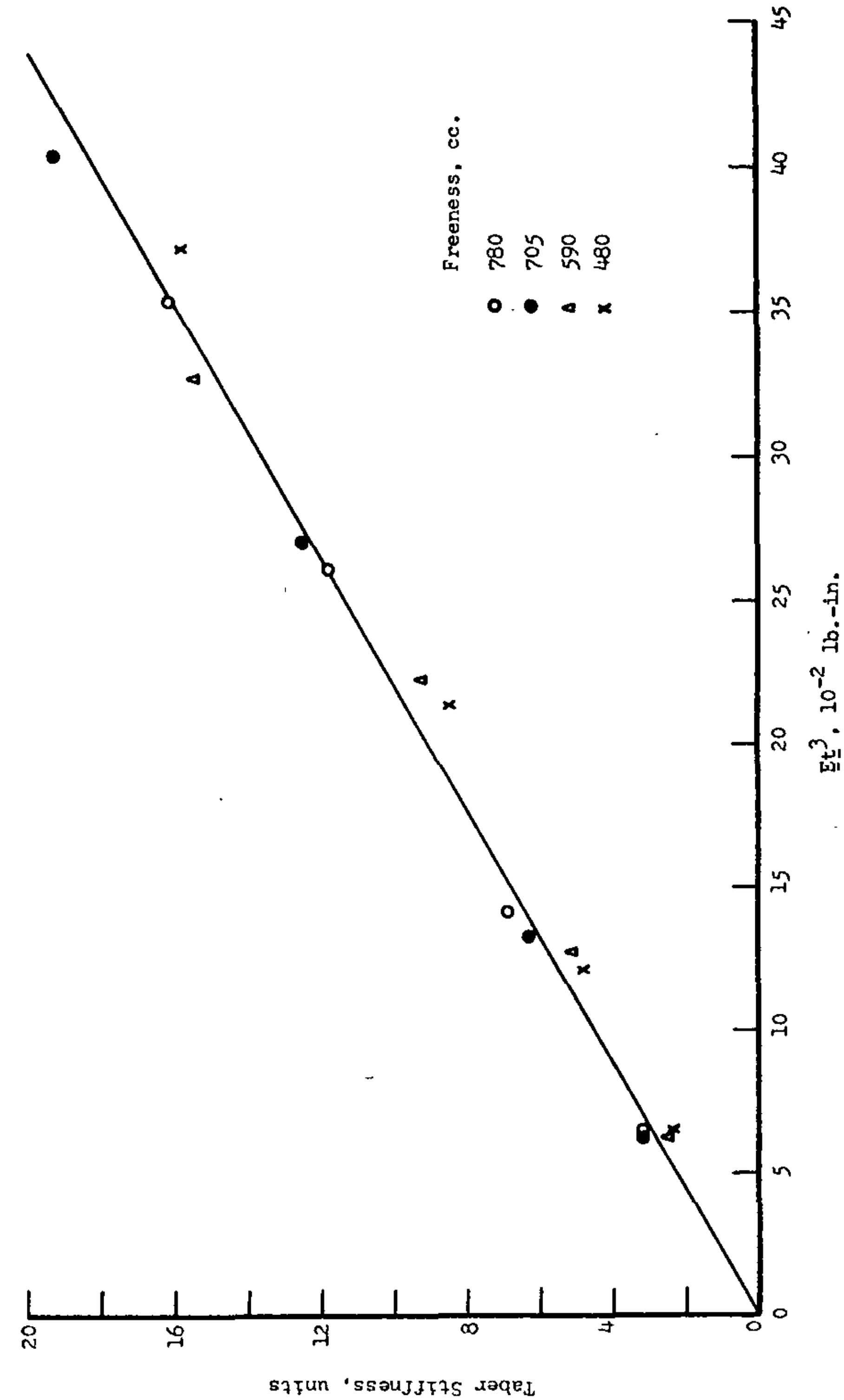

Figure 9. Relationship Between Taber Stiffness, Modulus of Elasticity, and Caliper

under study in the research program, namely, modulus of elasticity and caliper. As shown earlier, the modulus is essentially independent of basis weight and, as shown in Fig. 10, caliper increases linearly with basis weight. Thus, variation of basis weight in the range of 14 to 27 lb./1000 sq. ft. has a predictable effect on Taber stiffness.

The z-direction tensile test has been under development at The Institute of Paper Chemistry with the objective of devising a method of measuring bonding strength in a sheet of paper or board. Although the test method has not yet reached full development, particularly in regard to its interpretation, it was included in the present test program for the possible insight it may afford with respect to transverse bond strength. The latter is believed to be a major factor in the edgewise compression strength of a component.

Table X presents the results of the z-direction tensile test. It will be seen that three of the entries are missing. These correspond to sheets of low basis weight where evidence of complete penetration of the epoxy resin throughout the specimen thickness was noted, thereby invalidating the test method. In two other instances, penetration occurred on one or more handsheets out of the sample of ten.

Inspection of Fig. 11 reveals that z-direction tensile decreased with increase in basis weight. Ostensibly this result indicates poorer bonding at higher basis weight, although there is some question whether the trend may reflect a stress concentration effect due to fiber flexing in the thicker sheets, which is not indicative of bond strength.

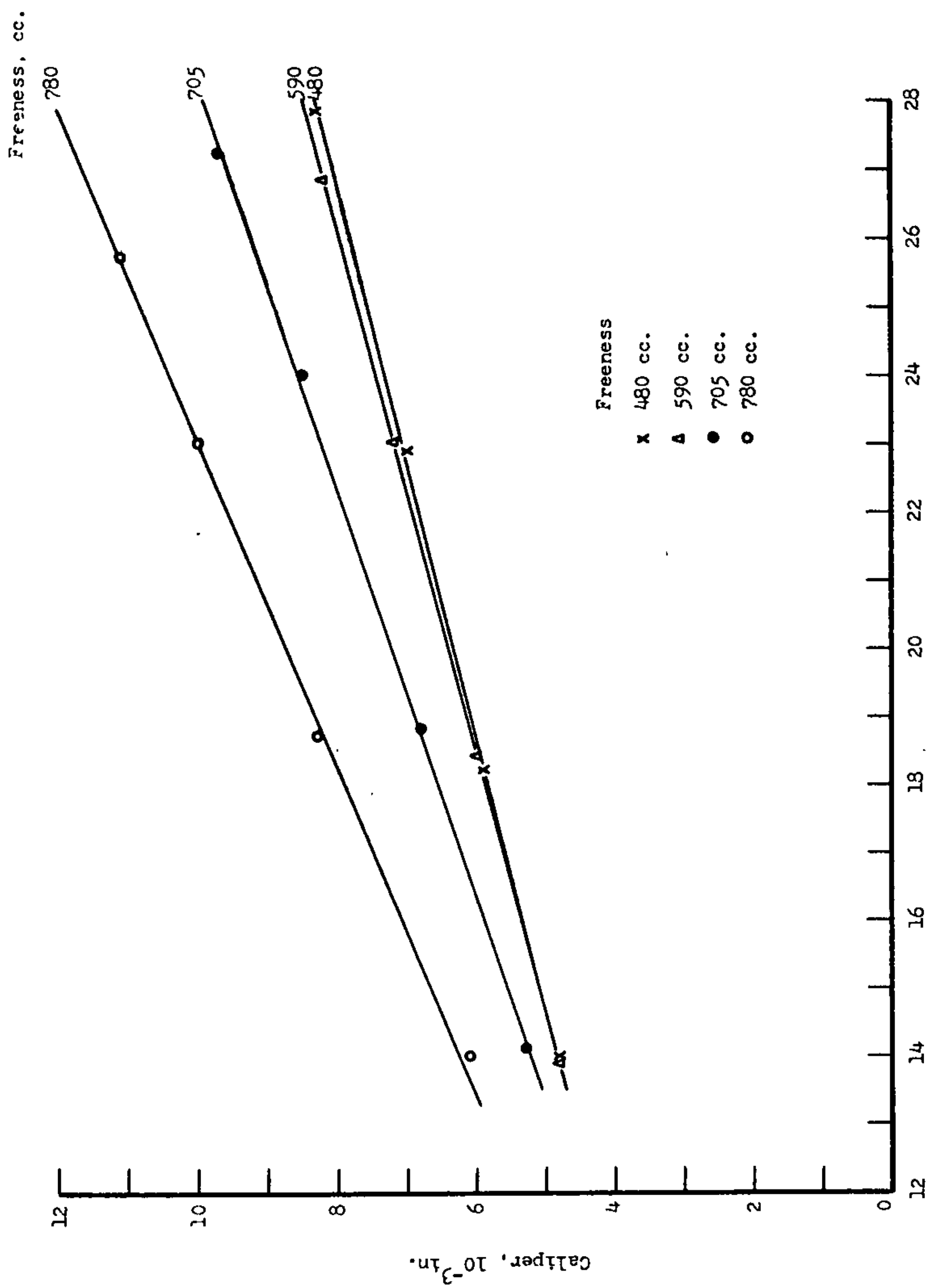

Figure 10. Relationship Between Caliper and Basis Weight

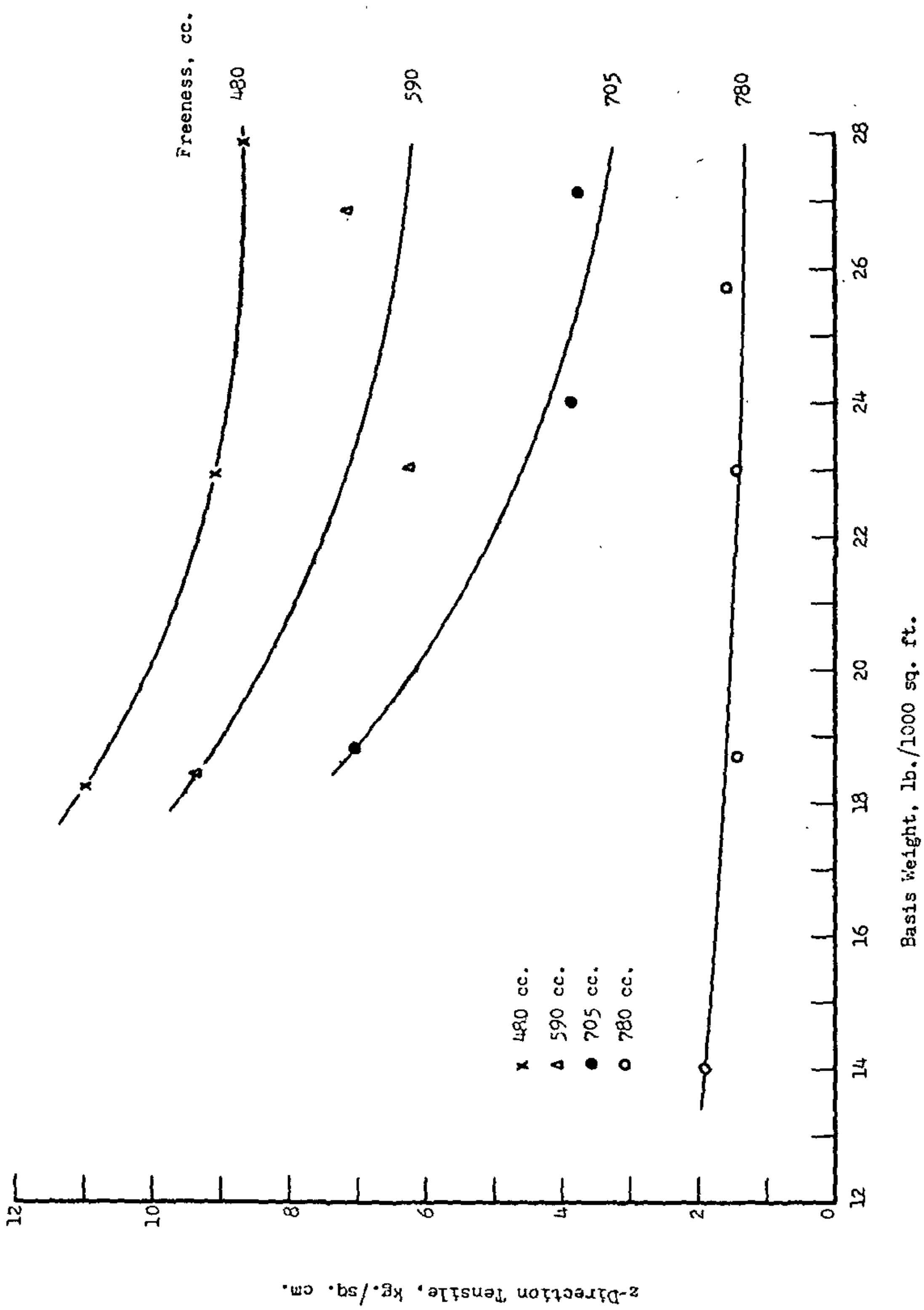

Figure 11. Relationship Between z-Direction Tensile Strength and Basis Weight

TABLE X

z-DIRECTION TENSILE STRENGTH OF HANDSHEETS

	z-DIRECTION TENSILE, kg./cm.^{2}				
	Average Basis Weight Level, lb./1000 sq.ft.				
Freeness, cc.	14	19	23	27	Av.
780	1.93	1.48(9)[b]	1.46	1.60	1.62
705	--[a]	7.05(6)[b]	3.88	3.79	4.91
590	--[a]	9.35	6.28	7.16	7.60
480	--[a]	10.97	9.10	8.69	9.59
Av.	1.93	7.21	5.18	5.31	5.60

[a]Resin penetration on all specimens.
[b]Specimens with resin penetration excluded.

Figure 12 indicates that z-direction tension increased markedly with degree of refining, which is consistent with the expectation that more numerous and/or stronger bonds are formed as refining is increased. Moreover, the decrease in caliper associated with increased refining would be expected to diminish the stress concentration effect and thereby increase z-direction tensile.

INTERRELATIONSHIPS BETWEEN MECHANICAL PROPERTIES OF COMPONENTS

The foregoing section of this report was concerned mainly with the effect of basis weight and degree of refining on the physical properties of components. This section presents several interrelationships between the mechanical properties. These relationships are of interest for several reasons. In some cases, theory or previous experience indicates that certain relationships should hold. The

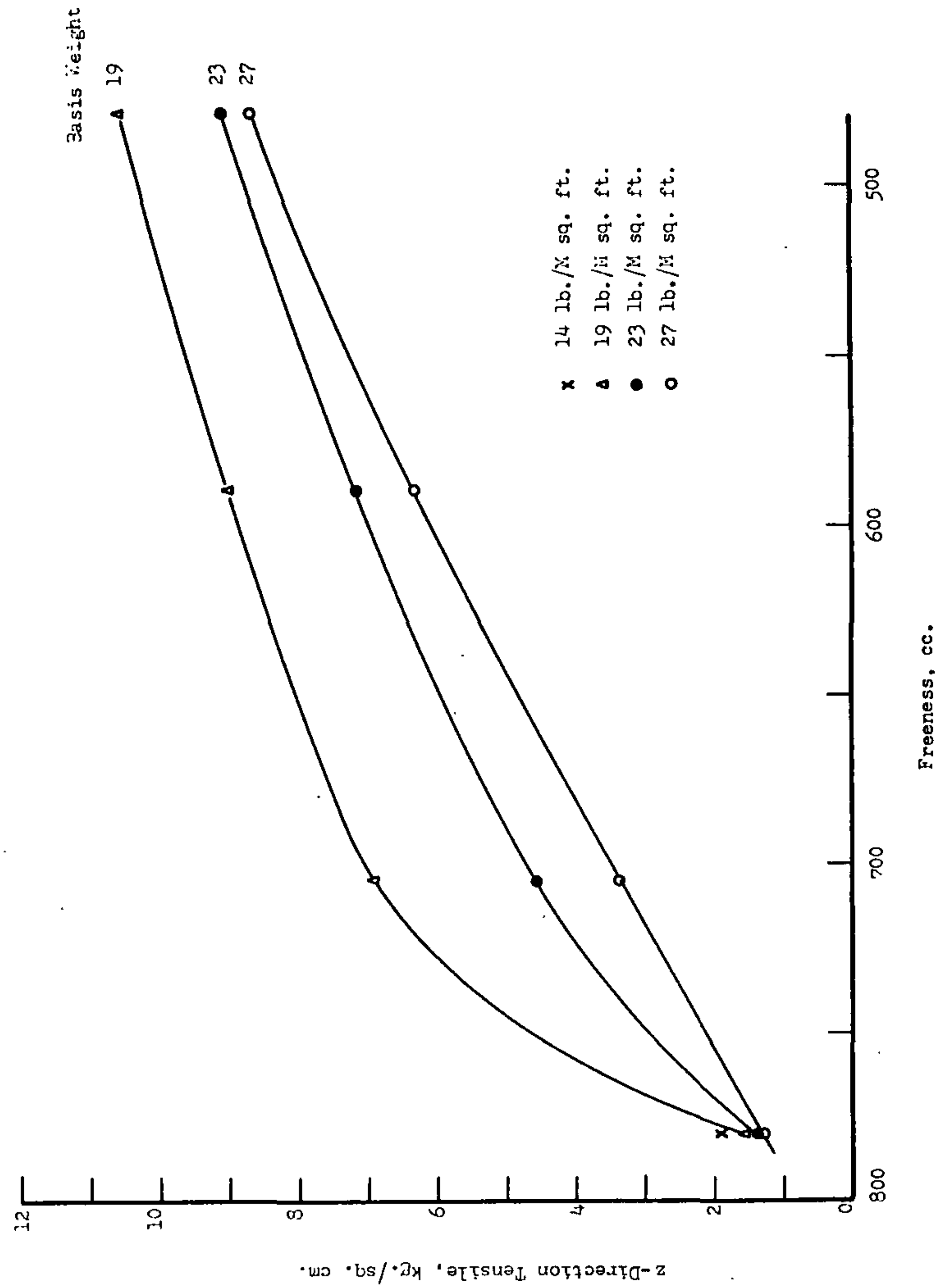

Figure 12. Relationship Between z-Direction Tensile Strength and Degree of Refining

previously discussed case of Taber stiffness vs. Et^3 (Fig. 9) is an example. In such cases, the interrelationships furnish a check on the validity of the experimental data. Moreover, such relationships may be of practical use to the experimenter or mill research personnel in reducing the number of variables which need to be studied.

One relationship of considerable theoretical interest is given in Fig. 13. This graph shows a strong relationship between modified ring compression and extensional stiffness Et. Interest in this relationship dates back to the development of the abridged formula for top-to-bottom compression. It may be recalled that the formula for box compression was further simplified on the basis of an empirical correlation which was observed between flexural stiffness, edgewise compression and caliper of combined board. It was pointed out at that time that the implication of the correlation was that there must be relationship between edgewise compression and extensional stiffness of linerboard (1). This implied relationship appears now in the present controlled experiment on component properties and, therefore, lends confidence to the development of the abridged box formula.

The relationship shown in Fig. 13 between modified ring compression and extensional stiffness should be regarded as strictly a correlation rather than a causal relationship. Extensional stiffness is an elastic property whereas edgewise compression is a rupture property. The relationship implies that a "stiff" component is also a "strong" component, but other than this association, the two properties reflect different aspects of component behavior. Ultimately, both are undoubtedly related to fiber characteristics and/or bond strength and this probably accounts for the correlation. It may be recalled that both properties varied in about the same manner with change in basis weight and freeness.

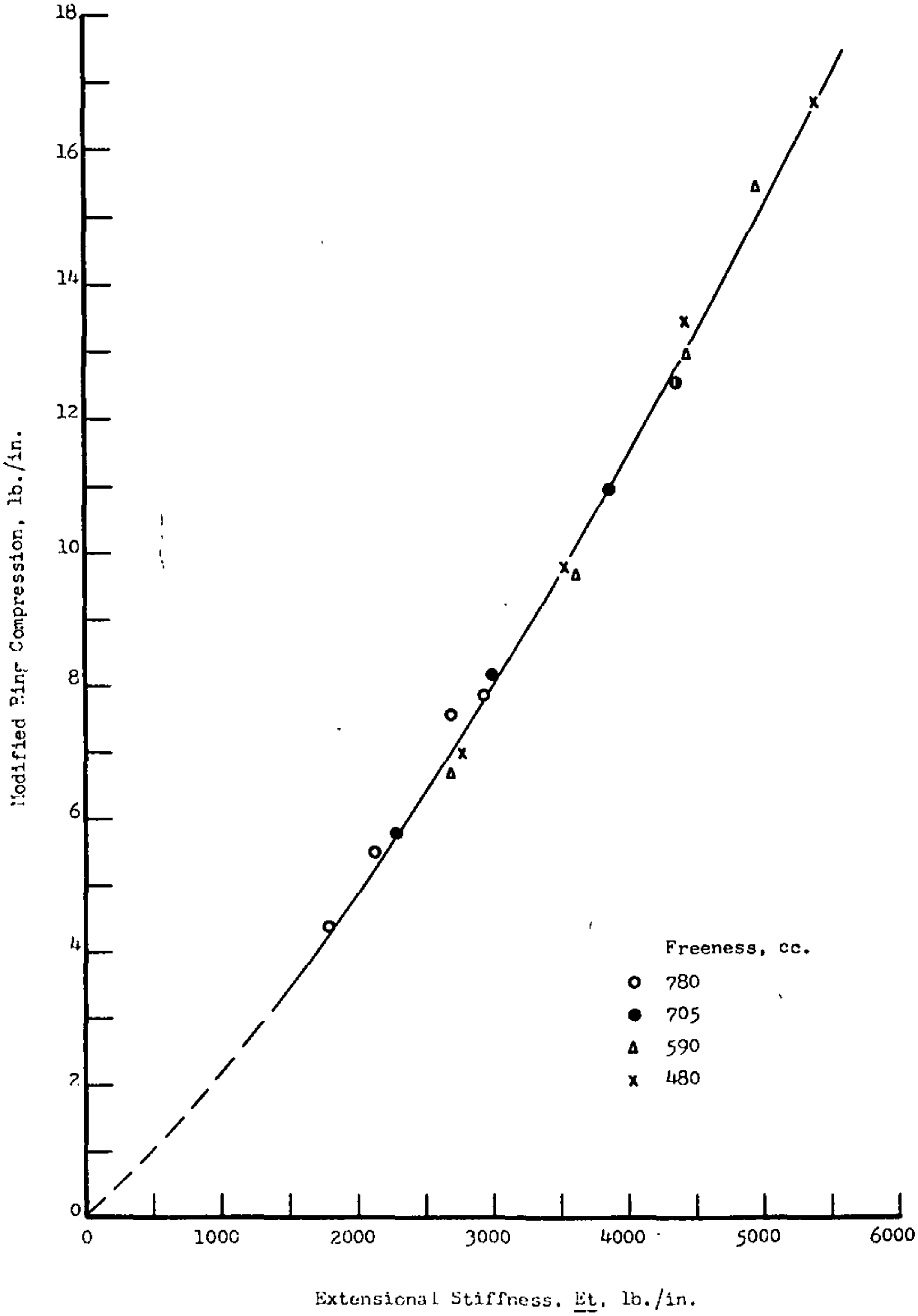

Figure 13. Relationship Between Modified Ring Compression and Extensional Stiffness

A recurring question is whether the modified ring compression test measures the flexural rigidity of the component rather than its axial, edgewise crushing strength. Indeed, a major burden in developing an adequate compression test is to ensure that the specimen will crush rather than bow or bend as an "Euler long column."

Figure 14 shows the relationship between modified ring compression and Taber stiffness. The fact that these curves are not straight lines indicates that the specimen does not behave as an Euler column, because the strength of the latter is directly proportional to flexural stiffness. Moreover, flexural stiffness (Taber) alone would suffice to describe the strength of an Euler column and there would be no separate dependence on level of refining, in contrast to the effect of refining on modified ring compression which is evident in Fig. 14.

Figure 15 shows the relationship between modified ring compression and z-direction tensile at various levels of basis weight. Assuming z-direction tensile to be a measure of transverse bonding, the graph shows the expected trend to higher ring compression as the z-direction tension increases. It is suggested that further attention be given to graphs of this type in future work because they possibly involve appropriate sheet factors for describing modified ring compression, that is, a measure of the quantity of fiber (basis weight) and a measure of the bonding between fibers (z-direction tensile).

Lastly, Fig. 16 shows the relationship between modulus of elasticity and density of these handsheets. Over the years a number of investigators have cited a linear relationship between these two sheet properties [see, for example, (5,6)]. The data of this experiment exhibit considerable divergence from a straight line at the higher levels of refining.

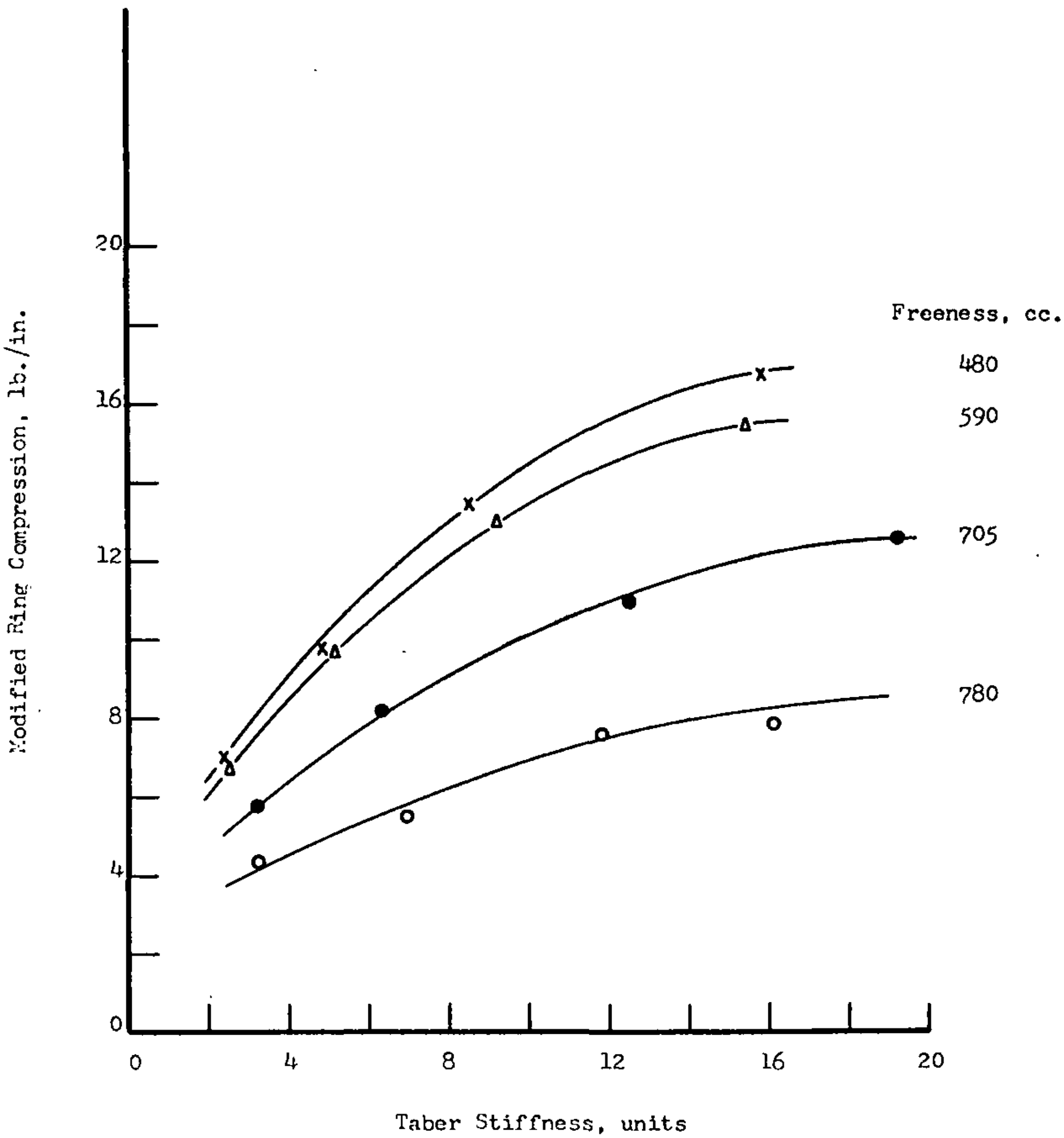

Figure 14. Relationship Between Modified Ring Compression and Taber Stiffness

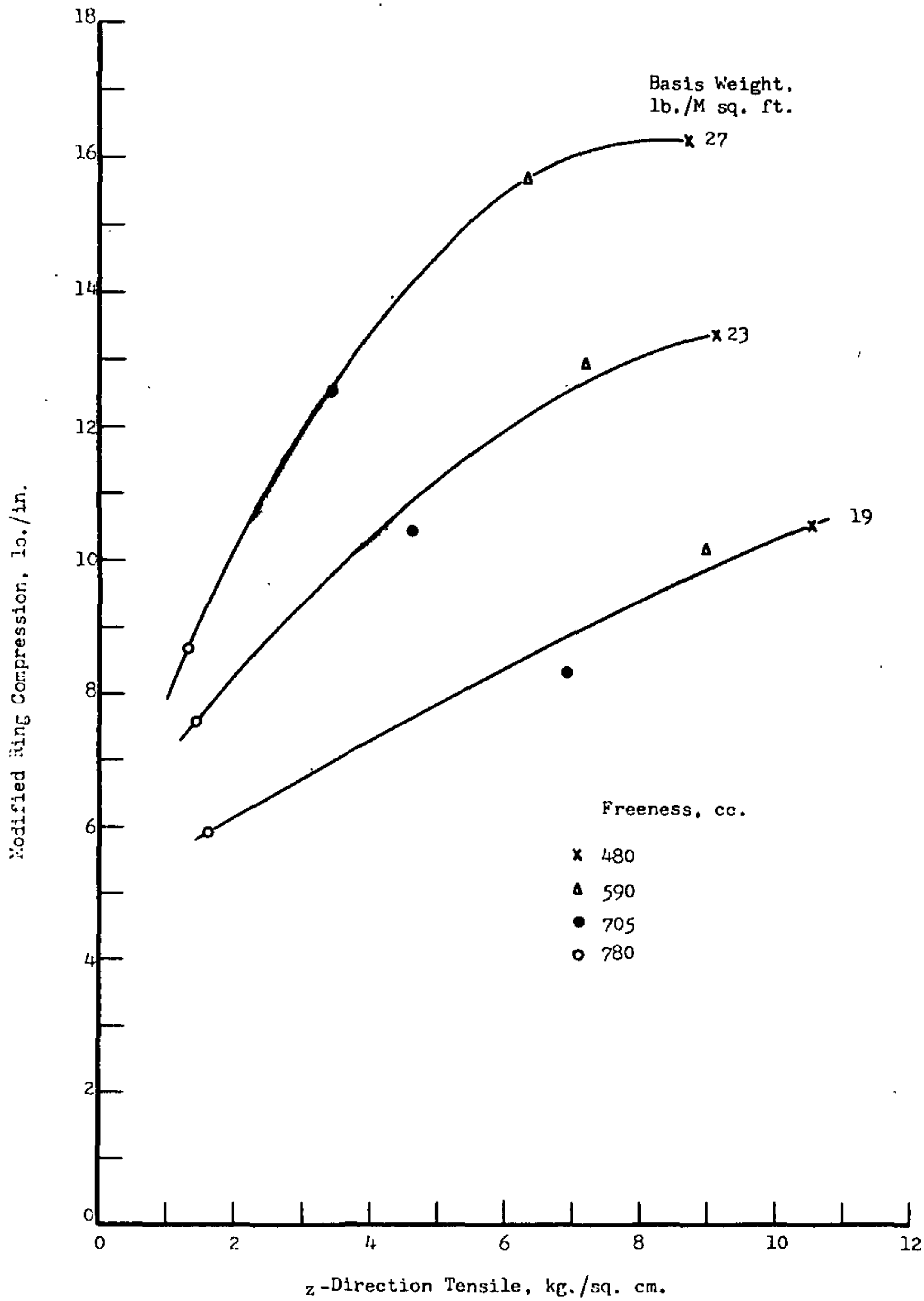

Figure 15. Relationship Between Modified Ring Compression and z-Direction Tensile Strength

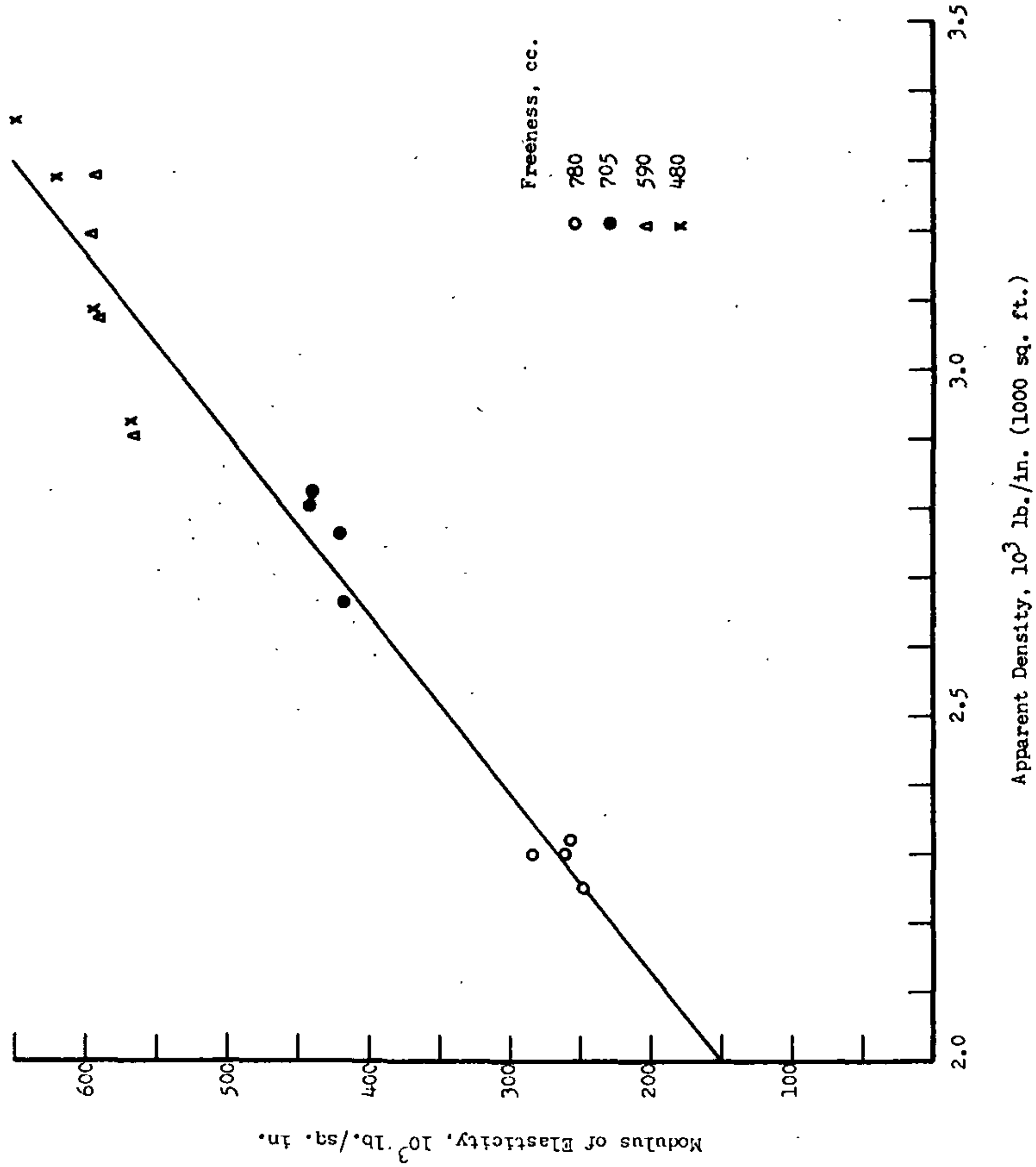

Figure 16. Relationship Between Modulus of Elasticity and Apparent Density

FUTURE WORK

It has been found in the work described above that the mechanical properties of components which are of importance to box compression performance vary linearly with, or are independent of, basis weight in the range of basis weights from 14 to 27 lb./1000 sq. ft. (An exception was Taber stiffness, but this property is governed by other properties which are linearly related to basis weight.)

The requirement for laminating that the mechanical properties be proportional to basis weight was not fulfilled in the case of modified ring compression. However, it is believed that sheets of commercial weights can be laminated from handsheets by using the same number of plies in each construction. This technique should give built-up sheets of varying basis weight which are not influenced by the worsening formation usually experienced in commercial linerboards.

The next phase of this study will involve preparation of handsheets having basis weights in the range of 26 to 90 lb./1000 sq. ft. The relationship between the mechanical properties and basis weight will be studied, thereby revealing the effect of the amount of fibrous material on component properties important to box compression. Single-ply handsheets will also be made in the same basis weights and a comparison of the results of the two techniques should delineate the separate roles of (a) quantity of fiber, and (b) formation.

Subsequent phases of the study will be concerned with the effects of fiber variables and process variables, as enumerated in the Introduction to this report.

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