Corrugating Medium Reference

Its Influence on Box Plant Operations and Combined Board Properties and Package Performance

Project 3808

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of
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Introduction

The purpose of this publication is to provide a comprehensive review of the technical information available on the corrugating process, combined board strength, and package performance as impacted by the corrugating medium. The technical information reviewed covers both the effect of medium material properties and the effect of the corrugating process variables as they interact with the medium. While this publication emphasizes the work done at the Institute of Paper Science and Technology, it also includes extensive information from other published sources. A bibliography of 178 articles spanning the period from 1939 to 1993 and which includes subject matter related to corrugating medium was compiled.

This publication is not a comprehensive encyclopedia on corrugating medium. It does, however, discuss the major observations and conclusions from this body of research with enough detail to qualitatively and quantitatively demonstrate cause and effect relationships. The reader should keep in mind that the quantitative relationships are specific to the experimental conditions used in each reference, and while the trends shown are probably valid for a wide range of operations, each specific operation may find the magnitude of the effects to be greater or smaller. The reader can obtain the detailed experimental conditions, the detailed mathematical equations, and the detailed experimental data from the references cited.

The reference bibliography is presented in chronological order starting with the most recent publication. A bibliographical subject index and a bibliographical author index are included to assist you in researching specific subjects. The references cited in the bibliography may also be a source of additional references not included in this bibliography.

Paper, as we know it, made from a slurry of plant fibers filtered through a mesh, pressed, and then dried, was first produced in China in the second century B.C. It then took 21 centuries for corrugated paperboard to be invented. Albert L. Jones obtained a patent in 1871 which covered the production of fluted paper without the facings being attached. The idea for fluting paper was an offshoot of the method used to maintain the ruffled collars worn by the 18th century gentlemen, (106).

The rapid growth of corrugated packaging technology then followed. A patent for single-faced corrugated, used primarily for protecting glass lamp chimneys, was issued to Oliver Long in 1874, and was followed by a patent for singlewall corrugated granted to H. B. Meech in 1879. The first use of corrugated shipping containers was in 1903, for transporting dry cereal by rail. The Western railroads established a Rule 41 for corrugated shipping containers in 1906. This grudgingly recognized the corrugated case as an alternative to wooden crates. The only requirement was that the package weigh no more than 100 pounds. The Southern railroads joined the Western railroads in accepting products in corrugated boxes in 1910. Rule 41 was modified to establish a corrugated board grade structure based on box size, package weight, mullen burst strength, and the caliper of the facings, (106).

It took a decision by the Interstate Commerce Commission in 1912, to require all railroads in the United States to accept, without prejudice, corrugated paperboard shipping containers as an alternative to wooden crates. This was known as the Prindham Case, and it established a uniform, nationwide grade structure for corrugated, a United States Rule 41. The legal ability of the railroads to set these packaging specifications was based on the anti-trust exemption granted to the Uniform Classification Committee by the U.S. Congress. When truck carriers became prevalent, a similar arrangement was established for this mode of transportation, and its packaging specification is known as Item 222.

Over the years, additional grades were added to Item 222/Rule 41, such as doublewall and triplewall, and other minor changes were made. However, during the 71 years between 1912 and 1993, only two major changes to the corrugated board grade structure specification format were made. Linerboard basis weight was substituted for the linerboard caliper in 1944. This change was in response to the increasing use of the fourdrinier paper machines as replacements for the cylinder paper machines in the 1940s. The linerboard produced on the fourdrinier was able to meet the mullen burst specification at a lower basis weight and, therefore, lower caliper than the cylinder machine linerboard. This reduction in basis weight allowed the linerboard productivity and capacity improvements that were needed to provide sufficient corrugated boxes to support the material logistics of the World War II effort. The second major change occurred in 1991, when Edge Crush Test was adopted as an alternative to the combined board mullen burst test and the linerboard basis weight, (6, 106). This change reflected the importance of the top-to-bottom compressive strength of the box for meeting today's performance requirements.

You have probably noted that, except for a minimum basis weight of 26 lb/msf and a minimum caliper of 9 mils for the medium, the Item 222/Rule 41 corrugated board grade specifications involved physical properties related only to the linerboard component of corrugated board until 1991, when the Edge Crush Test option was added. The medium was considered an "ugly stepchild," at best, by the non-technical community of our industry. It is a component not readily visible in the finished product. You might say "out of sight, out of mind." Recycled or Straw medium was the product of the day for 75 years. The first commercial semichemical medium, Neutral Sulfite Semichemical (NSSC), was not readily available until 1946, (6).

Corrugating medium is still not considered a very glamorous product and is still not a very attractive looking paper. However, glamorous or not, attractive or not, the corrugating medium is what makes the product a corrugated board. Without the medium, the product would be either a solid fiber box or a paper bag. Knowledgeable people have opined that corrugated board is a sandwich structure in which the medium is the meat of that structure, (7). It has also been stated that "The quality of corrugated board is determined on the single-facer because it is here that the operation should develop the maximum potentials of the medium," (129). The medium must maintain the separation of the linerboard facings to form a sandwich structure. It must do this after being burned on preheater drums; scalded with steam showers; pulled, bent, and squashed in the corrugating rolls; doused with a watery starch mixture; and flat crush compressed in the hot plate section of the double-backer and in the finishing department.

The life of the corrugating medium is not an easy one. It must be weak enough to flute, but strong enough to withstand the tensile, the flat crush, and the edge compression forces. It must be absorbent enough to condition in the steam showers but remain nonabsorbent enough to form and maintain strong corrugator bonds. It must be slippery enough to minimize the tensile forces developed in the single-facer operation, but have a high enough coefficient of friction to prevent the rolls from telescoping while being handled. The key to a "good" corrugating medium is the balance of properties.

The format used in this publication is to follow the life story of corrugating medium starting with the flute formation in the box plant and ending with the medium's contribution to the field performance of the corrugated box. Each chapter is devoted to a specific step in this total medium process.

I have attempted to use my experience and judgement in interpreting the significance of the information given in the references. However, in the few instances when the literature indicated conflicting conclusions that could not be logically reconciled, both conclusions are presented for the reader's consideration. Again, the reader should keep in mind that the quantitative relationships shown are specific to the experimental conditions and materials used in each reference. While the trends shown are probably valid for a wide range of operations, each specific operation may find the magnitude of the effects to be greater or smaller than shown by the specific data.

Chapter 2

Flute Forming Theory

It has been suggested that the quality of the corrugated board is determined at the single-facer. The objective of the single-facer operation should be to maintain the maximum strength and quality potential of the medium, (129).

In the common parlance of the corrugated industry, the performance of the medium in the single-facer operation is known as "runnability." The concept of runnability encompasses only the needs and requirements of the corrugating crew and corrugating operation. A good runnability medium does not necessarily indicate a good performance package since the material may be weak in strength properties. A poor runnability medium does indicate a potential for a poor quality package. In some instances, the corrugator crew can overcome the potential package quality problems associated with the poor runnability by making compensating adjustments to other factors in the corrugating process, such as slowing the corrugator speed. In this event, the package quality does not suffer, but the medium still has poor runnability in the eyes of the operator and in the eyes of the box plant cost accountant.

If a specific medium is said to have "good runnability," there is no problem in understanding that the medium performed well and without problem during corrugation. Unfortunately, the term "poor runnability" does not convey a specific definition as to what problems were encountered. There are many symptoms each of which, by themselves or in combination with other symptoms, represents poor runnability.

The term "runnability" encompasses two major performance criteria: Flute Formation and Bonding. The Flute Formation criterion includes two subcategories: Fractured Flutes and High/Low Flutes. Both of these defect categories are influenced by the medium physical properties and attributes, by the corrugating process settings, and by the mechanical condition of the corrugating equipment. The fluting process is considered the key element for box plant productivity and the structural performance of the package, (24, 25, 26, 27, 31, 38, 78, 84, 129).

The Bonding criterion also includes several subcategories such as blisters, fluff out, and loose edges. The bonding criterion will be discussed in later chapters.

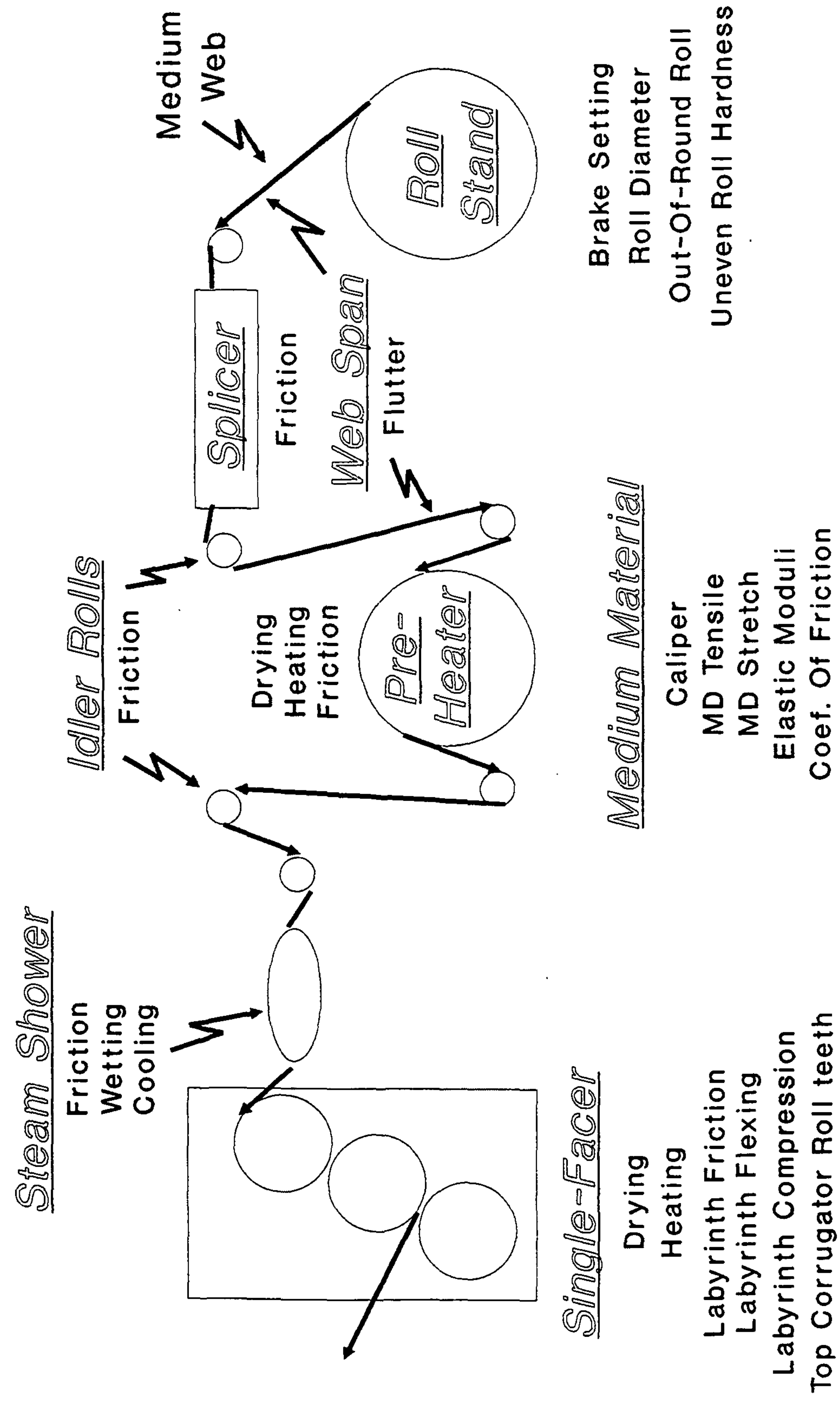
A simplified schematic representation of the single-facer corrugating process is shown in ***Figure 2.1***. The total process with regard to runnability includes factors existing at the roll-stand, the splicer, the preheater, the steam shower, the single-facer, and the various web spans and idler rolls, (154).

The process starts with the roll of medium in the roll-stand. The process variables at this point include the medium material properties, the medium roll quality attributes, and the roll-stand braking system. The medium properties that have been related to medium runnability include MD tensile, MD stretch, caliper, coefficient of friction, MD modulus of elasticity, ZD modulus of elasticity, MD/ZD shear modulus, and compressibility, (24, 78, 84, 134, 154). The medium roll quality attributes that are of concern include out-of-round rolls, uneven hardness across the roll, and roll edge damage. An out-of-round roll will lope as it unwinds and will cause tensile force spikes in the medium web. The uneven roll hardness will cause variability in the tensile force across the web width. Edge damage to the roll can initiate web breaks.

The roll-stand braking system affects the overall, average web tension by the adjustment of the brake setting. "Catching" of the braking system due to a mechanical defect will cause tensile force spikes in the medium web. The diameter of the medium roll interacts with the roll-stand braking system, depending on the specific system design, to increase the medium web tensile force as the roll diameter decreases. The medium roll is turned on the roll-stand by the pull force of the medium web as it feeds through the corrugating rolls. If the roll-stand brake resistance force is fixed and constant, the leverage arm of the medium web pulling force (roll radius) decreases as the paper is consumed and the roll diameter decreases. The medium web tension must then increase proportionally to the decreasing

FIGURE 2.1

Schematic Diagram of Single-Facer Forces and Material Factors



leverage arm in order to keep the pulling force needed to overcome the brake force constant and to keep the roll unwinding.

The splicers are generally designed so that the hydraulic system controlling the festoon adjusts the pressure to keep the idler rolls properly spaced. These adjustments can add tensile force spikes to the medium web. The splicer idler rolls, as well as all of the other idler rolls in the single-facer, increase the web tension due to friction in the bearings. The tensile loading that is of concern is the tensile force per inch of medium web width. The roll-stand braking resistance for a given setting and the frictional resistance at the bearings are generally independent of the medium web width. Therefore, the tensile force per inch of the medium increases as the medium web width decreases. A one-setting-fits-all approach to medium web tension control at the single-facer is not a recommended operating strategy to follow as the medium web width varies. The free spans of the medium web between idler rolls also add to the tensile force due to the force of gravity on the mass of the medium. Typical, relative tensile forces for a single-facer are shown in ***Table 2.1***.

Table 2.1. Relative Tensile Forces Generated In The Single-Facer, (154)

Process Stage	Relative Tensile Contribution
Roll-Stand & Roll	300 units
Preheater	15 units
Idler Rolls (Total)	23 units

The preheater drum will also add to the web tension due to the medium having to turn the drum. Some plants lock the preheater drum so that it does not turn. This greatly increases the web tension since the medium must now be pulled over the heated surface. The locking of the preheater drum is usually done to compensate for a mechanical problem with the preheater. The steam shower also increases the medium web tension since the medium must slide across the surface of the device.

The single-facer variables are more complex. First, the medium web must be dragged across the flute tips of the upper corrugating roll so as to provide the material required to make the flute shape (draw factor effect). Second, the medium needs to be pulled over the tip and sidewalls of both corrugating rolls as the flute is actually being formed. Third, the medium is flexed as the flute is formed. Fourth, the medium is then compressed as the teeth of the upper and lower corrugating rolls come together at the nip.

The compression of the medium due to the corrugating roll pressure is shown in ***Figure 2.2***. The medium exhibits a permanent caliper loss of between 30% and 40% in the flute tip area and between 5% and 15% in the flute sidewall areas. The data indicate that the permanent caliper loss due to the medium compression is equal in magnitude for both the leading and trailing sidewalls of the flute. The average permanent caliper loss and the relative loss between the tip and the sidewall do vary with different flute size corrugating rolls. The direction of the observed differences, however, is not consistent with the difference in flute height. It appears that the differences are associated with the specific design of the corrugating roll flute contour, clearance, and radius of curvature, rather than flute size, A, B, or C, (145, 149).

The compaction of the fluted medium also appears to be influenced by the corrugator speed. In general, the permanent caliper loss appears to decrease as the corrugator speed increases. This speed effect observation may be explained by the effect of speed on the translational movement or bounce of the upper corrugating roll as the flutes of the two corrugating rolls mesh. This translational movement has been shown to occur twice per flute, once at the flute apex and once at the flute root. The amplitude of this translational movement decreases as the corrugator speed increases, and the flutes are less completely formed, (149, 152).

Figure 2.3 shows the effect of the medium web tensile force on the measured draw factor. The data indicate that the draw factor increases as the web tension increases, with the measured draw factor increasing by 0.96% when the web tension was increased from 0 lb/inch to 1.5 lb/inch. Intuition would indicate that the opposite shuld occur. Logic would indicate that the medium stretches more as the tensile force is increased and, therefore, should provide more linear footage to make flutes. The experimental data appear to be an artifact of the measurement technique used. The linear footage of the medium was determined by the number of revolutions of a medium web idler roll, and the combined board linear footage was determined by the number of revolutions of the corrugating rolls, (134). The increased medium length due to more stretch at the higher tensile loading causes an increase in the idler roll rotation. A similar increase in the corrugating roll rotation did not occur. This indicates that the stretch in the medium web up to the point of flute formation is overshadowed by the stretching required to form the actual flute. This indicates that the medium web tension used in the single-facer process should be set solely on the basis of controlling the medium web and on the

FIGURE 2.2
Permanent Thickness Compression of Medium During Fluting

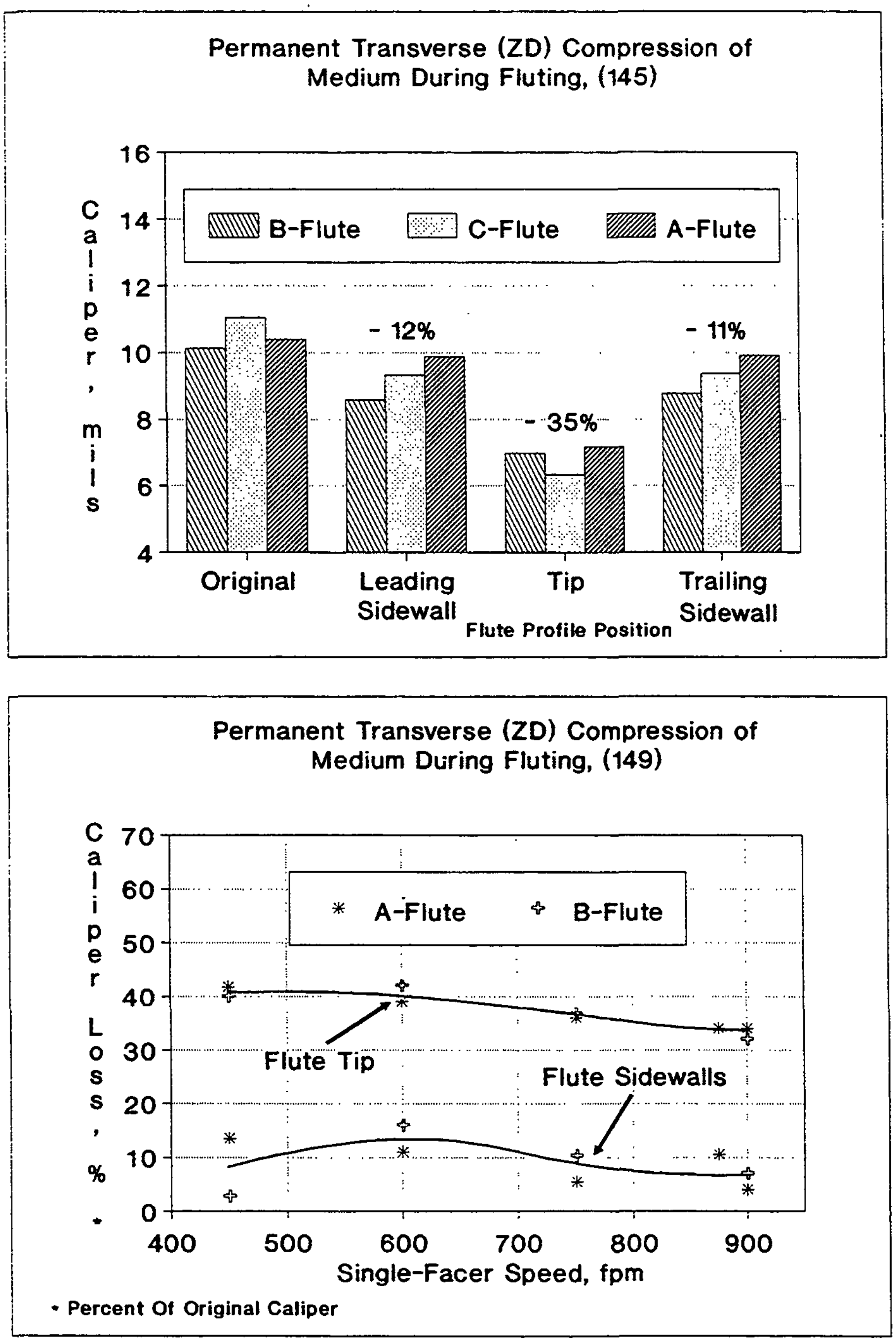
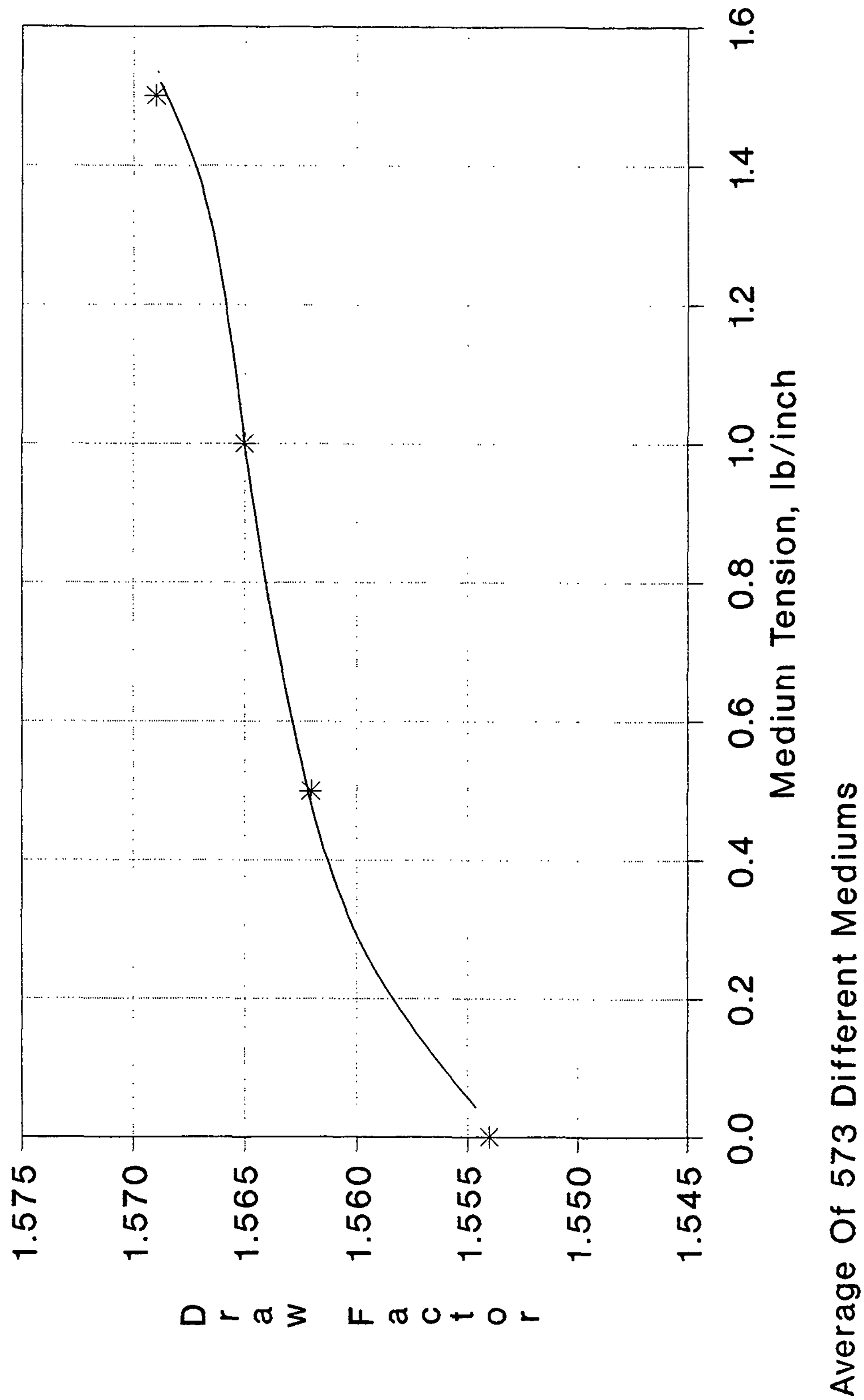


FIGURE 2.3
Effect of Medium Web Tension on Medium Draw Factor, (134)



basis of controlling the medium runnability. Using excessive medium web tensile force will not reduce material cost by reducing medium consumption.

The qualitative nature of the stresses on the medium during the flute forming process has been discussed in the literature. The medium web enters the single-facer by contacting a flute tip on the top portion of the upper corrugating roll. More linear footage of the medium is required to form the flute contour than is represented by the outer circumference of the upper corrugating roll. The medium must, then, be pulled over the tips of the upper corrugating roll teeth as it enters the labyrinth formed by the two corrugating rolls. As the medium enters the labyrinth, it contacts the teeth of the lower corrugating roll, and the medium web starts to be bent to form the flute shape. Based on the flute profile, the medium would have to be stretched by 8% to form the flute if no other strain relief mechanisms were present. Medium fails in tensile at approximately 1% stretch. Fortunately, there are other mechanisms. The bending and flute forming strains are accommodated by the medium pulling into the labyrinth, by the medium stretching, and by the MD/ZD shear of the medium, or, in the worst case, by fracture of the medium, (24, 129, 154).

There are also changes in the moisture content and temperature of the medium web due to the influences of the preheater, the steam shower, and the heated corrugating rolls. These changes can affect the runnability characteristics of the medium, (38, 78, 84). The specific effect of moisture content and temperature changes on the medium runnability is discussed in the following chapters.

Many of these forces applied to the medium during fluting alter the physical properties of the medium. These changes in the medium properties may help to explain why it is sometimes difficult to correlate the properties of the original medium to the medium runnability and the combined board properties with the degree of precision one would like.

The mechanical condition of the corrugator can also influence the observed runnability quality of the medium. Defective bearings can cause an increased tensile force on the medium web because of increased friction and can cause tensile spikes in the web if the bearings "catch." Run out in idler rolls and other rolls can also cause tensile spikes in the web.

Chapter 3

High/Low Flutes

The term "High/Low Flutes" refers to the variation in the height of the fluted medium component of the single-faced web. The quantitative level of high/low flutes is generally expressed as the difference in height between adjacent flutes. For a given sample of single-face board, it can be expressed as the average difference in flute height, or it can be expressed as the percent of flute height differences that exceeded a certain critical value. The most common critical value level used for comparisons is 4 mils.

The high/low flute defect is important because of its adverse effect on combined board strength properties and package performance. The variation in the flute height of the single-faced web results in either a variable strength double-backer bond or in excessive crushing of the flutes, (115). The variable double-backer bond strength is caused by the low height flutes receiving less adhesive applied to them than the taller flutes in the double-backer glue machine. Excessive crushing results when the corrugator crew increases the double-backer hold-down roll pressure so as to achieve a more uniform adhesive application. The increased pressure crushes the taller flutes to the height of the shorter flutes.

The effect of the high/low flute defect on the combined board Edge Crush Test (ECT) is shown in ***Figure 3.1*** for a 42-26-42 lb/msf, C-Flute corrugated board construction. The data show that the ECT decreases as the percentage of high/low flutes increases. Sensitivity analysis using the regression equation shows that an increase in percentage of high/low flutes having a height difference of 4 mils or more from 0% to 100% results in an 11% loss in ECT, (5). Based on the McKee box compression model, an 11% decrease in ECT will result in an 8% decrease in the top-to-bottom compressive strength of the package made from the lower ECT strength corrugated board.

Many corrugator crews are familiar with a technique used to qualitatively evaluate the corrugated board for high/low flutes during production on the corrugator. The technique involves soaking a piece of singlewall board in water to separate the double-face linerboard from the medium. The double-face linerboard is then sprayed with an iodine/iodide solution in order to stain the starch glue lines and to make them more visible. The presence of high/low flutes is indicated by the variability in the observed glue line widths. This procedure is valid only if the hold-down roll pressure on the double-backer glue machine has not been excessively increased so as to crush the tall flutes and, thereby, obtain a uniform adhesive application.

Statistical analysis indicates that approximately 101 consecutive flute height measurements are required in a given sample in order to obtain a reasonable quantitative measurement of the high/low flute defect. The difference in height between adjacent flutes is then obtained by subtraction to obtain a set of 100 data points. The population of flute height differences is the high/low flute data.

One experimental technique is to make the flute height measurements using a mechanical caliper gage. The measurement is made on the single-faced web and includes the thickness of the single-face linerboard. This experimental technique is very time- consuming and introduces extraneous data variability by incorporating the linerboard caliper variability into the measurements.

An alternative flute height measurement technique was developed at the Institute of Paper Science and Technology. The method uses a infrared laser displacement gage that measures the distance from the top of the unbonded flute tip to the bottom of the adjacent flute roots. The speed of the laser device allows numerous intermediate height measurements on the flute sidewalls to be collected at the same time. The laser measurement data are fed into a computer program which calculates the sample high/low flute property in any form desired (average, % of flutes above 4 mils, % of flutes above 3 mils, a histogram of the flute height difference distribution, etc). The computer program also allows the flute profiles to be viewed and examined for flute shape abnormalities. This laser measure-

FIGURE 3.1
Effect of High/Low Flutes on Edge Crush Test, (5)

Effect of Box Plant Process Variables
on Combined Board Edge Crush Test, (5)

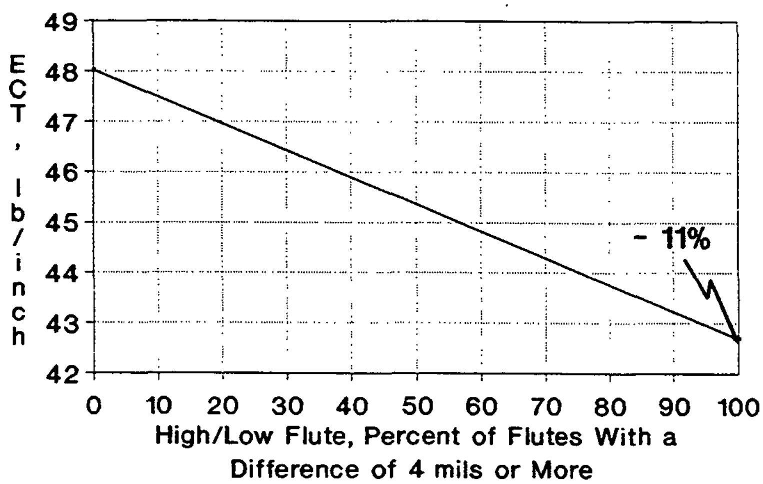
$$ECT = 33.7 - a(A) + b(B) - c(C) - d(D) - e(E)$$

$r^2 = 0.750$ $n = 216$

ECT = Edge Crush Test, lb/inch

a = 0.0397	A = Leaning Flute Angle, Deg.
b = 0.150	B = Single-Face Pin Adhesion, lb
c = 0.0534	C = High/Low Flutes @ 4 mils Or Greater, %
d = 0.134	D = Actual Crushing, mils
e = 0.130	E = Pressure Roll Cutting, % Mullen Loss

Effect of High/Low Flutes on
Combined Board Edge Crush Test, (5)
Sensitivity Curve



ment technique is quick, precise, and accurate, and is capable of making measurements at webs speeds in excess of 1000 linear feet per minute. The device is suitable for use in obtaining continuous high/low measurements on commercial corrugators, (24, 31, 72).

A high/low flute survey of 16 commercial corrugators was conducted in 1962. The results of the survey showed that all of the corrugators exhibited the high/low flute phenomenon and that there was a distinct pattern or periodicity to the high/low flutes on all 16 corrugators. The periodicity of the high/low patterns differed from corrugator to corrugator. These observations suggest that the presence of high/low flutes is more strongly related to the mechanics of the single-facer operation than to the nature of the corrugating medium material. The study also shows that A-Flute, B-Flute, and C-Flute samples exhibit approximately the same severity of high/low flutes and that the severity of high/low flutes can vary across a single-faced web at the same machine direction position, that is, a cross direction effect, (145).

Studies of the frequency of the corrugating medium web tension variability show that the dominant vibration component is at the primary flute forming frequency (corrugating roll teeth frequency) and its second, third, and fourth harmonics. The maximum amplitude of vibration occurs at different harmonics for different corrugator speeds. This suggests that the maximum amplitude is produced by the combined resonant frequencies of a number of corrugator components. The relative amplitude of vibration of selected corrugator components is shown in ***Table 3.1.*** The largest effect is associated with top corrugating roll pressure loading, (98). This effect is most likely related to the interaction of the corrugator roll pressure and the translational bounce of the upper corrugating roll associated with the rotational meshing of teeth with the lower corrugating roll.

Table 3.1. Relative Vibrational Amplitudes for Various Corrugating Components, (98)

Component	+/- Half Amplitude
Top Roll Acceleration	0.96
Top Roll Pressure	3.34
Web Tension	0.25

High-speed camera studies have shown that the high/low flute defect is associated with the process area located between the end of the lower corrugating roll fingers and the pressure roll nip where the fluted medium is suspended in air, (138). The proper positional adjustment of these fingers is important to controlling high/low flutes. The development of fingerless single-facers has reduced the high/low flute problem, but based on field experience, it has not completely eliminated the problem. Vibration of the upper corrugating roll, stresses at the pressure roll nip, and stresses associated with the angle of the web leaving the pressure roll nip also influence the tendency to have high/low flutes, (138, 149, 152).

Research has shown that the high/low flute defect is a result of single-facer mechanical conditions, single-facer operation settings, and the physical properties of the corrugating medium. A number of papers have been published which describe the influence of the various effects.

Figure 3.2 summarizes the results of a high/low flute study which utilized a modified laboratory concora tester. A strain gage was placed inside the concora tester and was used to measure the spring-back force of the fluted medium. The measurement was made at the exit side of the corrugating gears and simulated the response of the medium occurring in the gap between the end of the lower corrugating roll fingers and the pressure roll nip in the single-facer process. The researchers investigated the effect of medium moisture content, corrugator roll temperature, corrugator roll pressure, and medium web tension. All four variables had an effect on the spring-back force of the fluted medium. The order of impact of the variables, greatest to least, is the order as listed above. The high/low flute defect was reduced by a higher medium moisture content, a higher corrugating roll temperature, a higher corrugating roll pressure, and a lower medium web tensile force, (81).

Figure 3.3 summarizes the results of a high/low flute study conducted on a pilot size single-facer. Eight different commercial mediums were used in the study. The effect of the process variables of corrugating roll pressure, medium web tensile force, medium steam shower application, corrugating speed, and web take-off angle was evaluated. Take-off angle refers to the angle of the singlewall web leaving the pressure roll nip. The angle is expressed as deviation from the nip tangent line. All five variables had an effect on high/low flutes, and the order of impact of the variables, greatest to least, is the order as listed above. The high/low flute defect was reduced by a higher corrugating roll pressure, a lower medium web tensile force, a greater amount of preconditioning steam, a lower corrugator speed, and a lower take-off angle, (115).

Figure 3.4 and ***Figure 3.5*** summarize the results of a high/low flute study conducted on a pilot-size single-facer using several commercial mediums. The corrugating medium materials evaluated in the experiment included semichemical, kraft, and recycled fiber fur-

FIGURE 3.2
Effect of Corrugating Variables on Spring-back of Fluted Medium

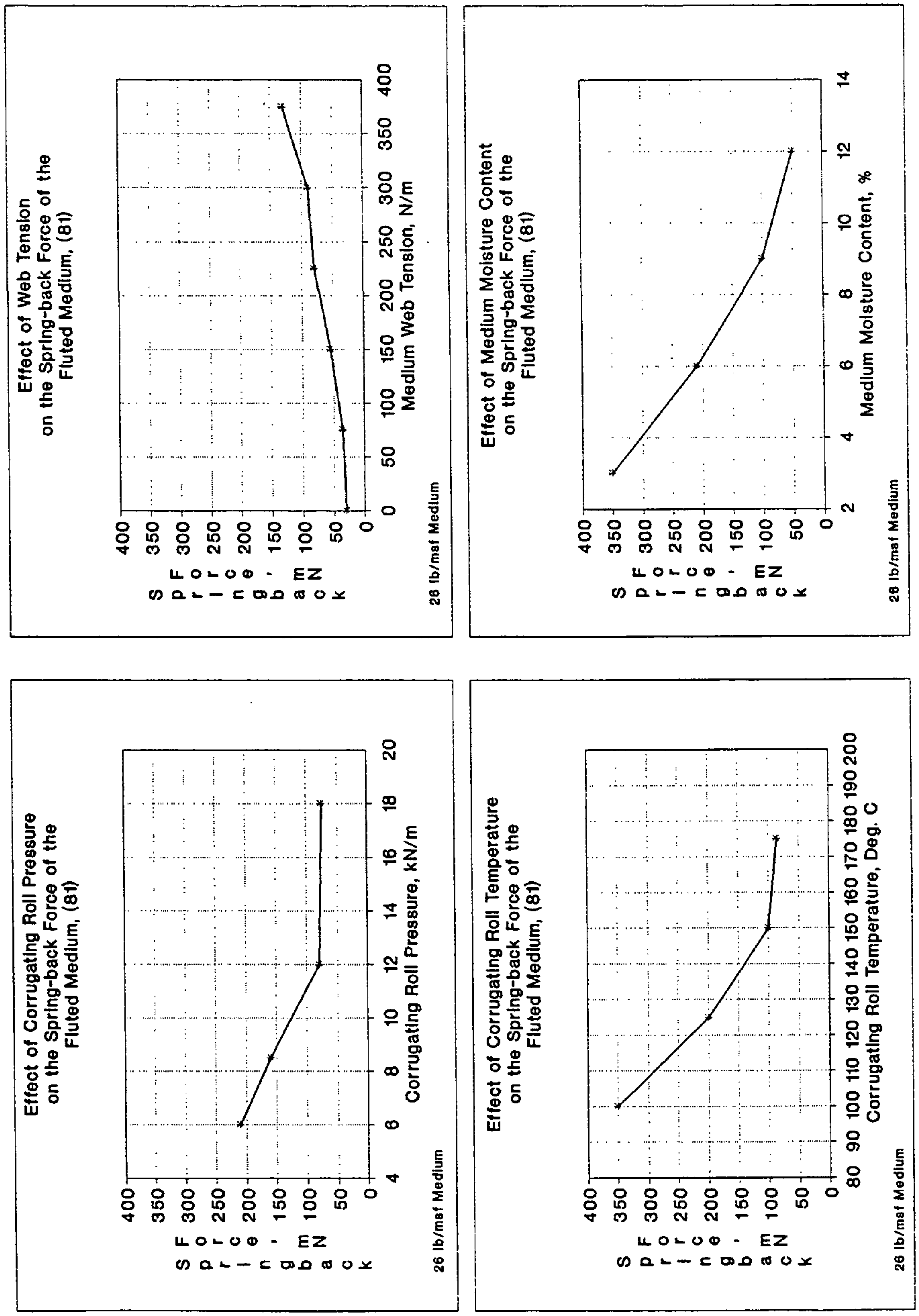
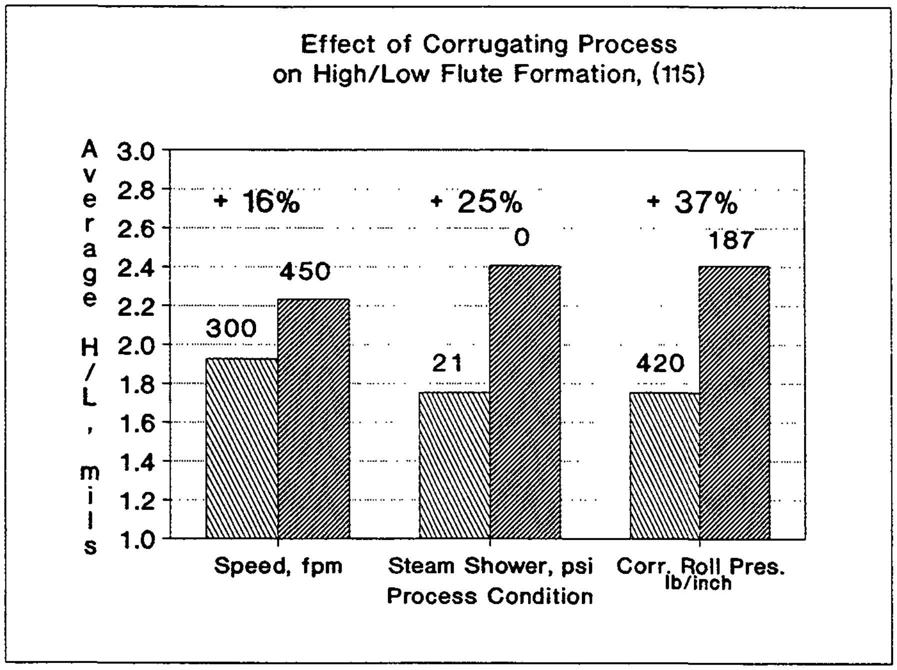


FIGURE 3.3
Effect of Corrugator Process Conditions on High/Low Flute Defect



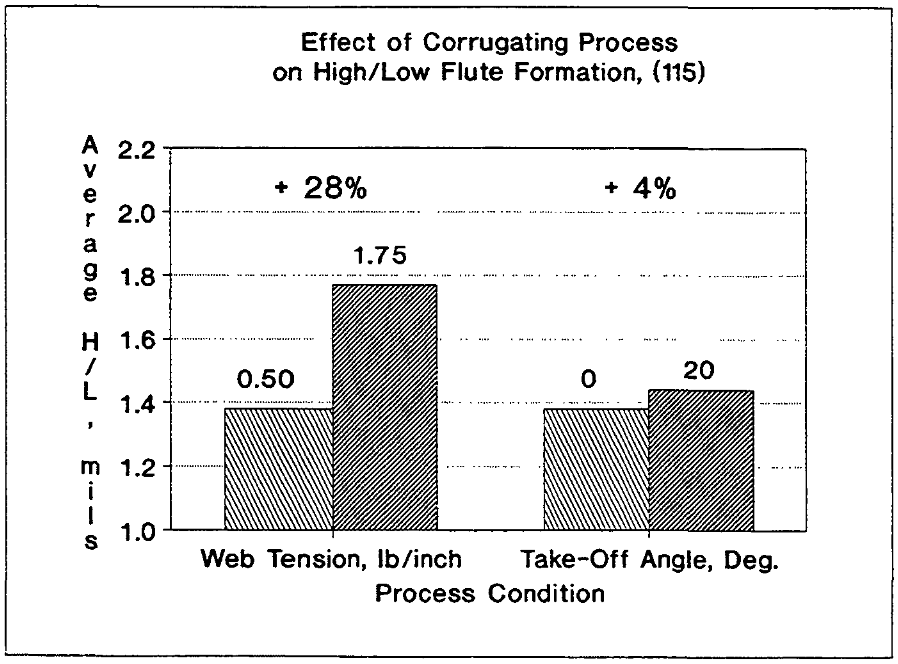


FIGURE 3.4
Effect of Corrugating Variables on High/Low Flute Defect

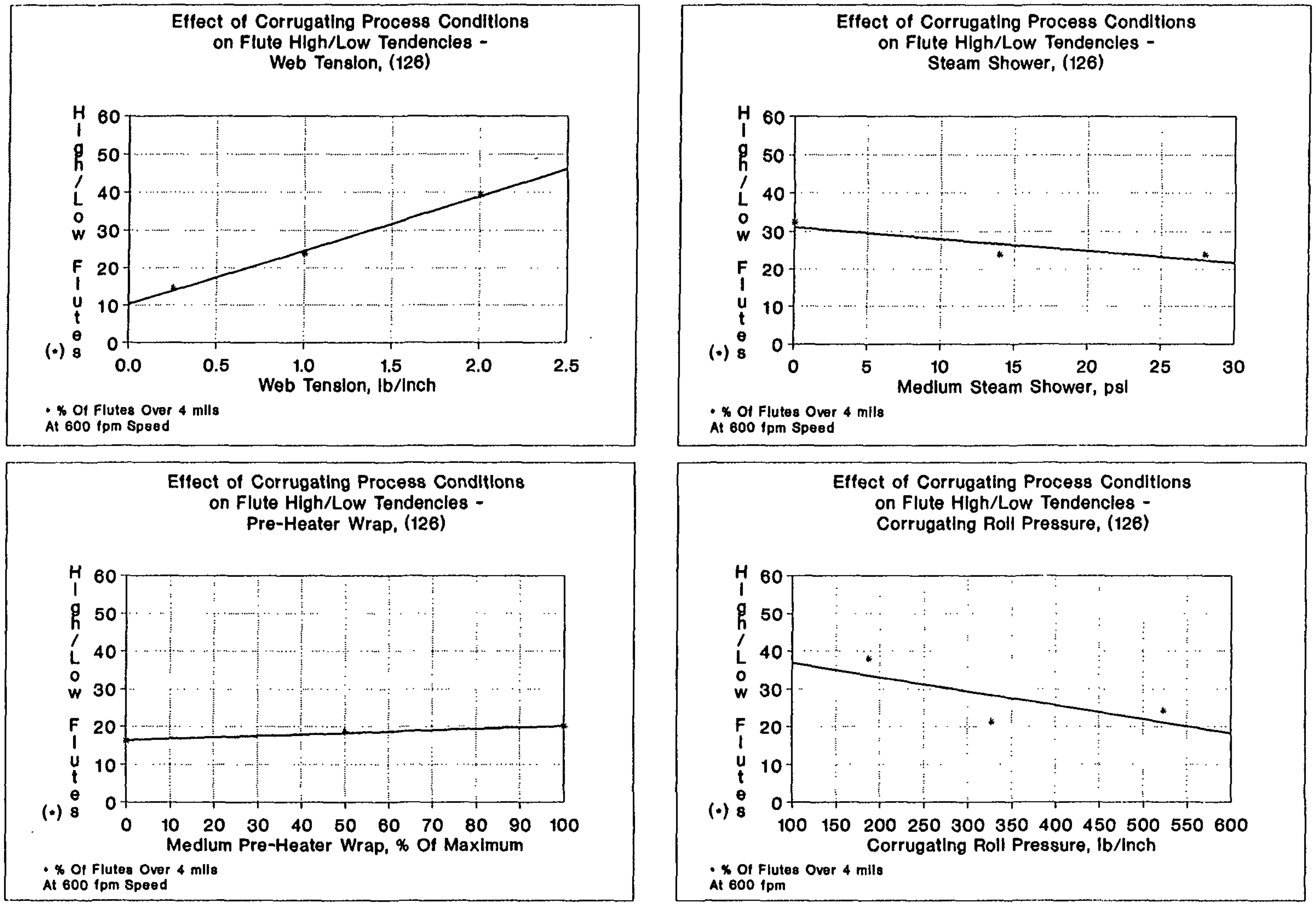
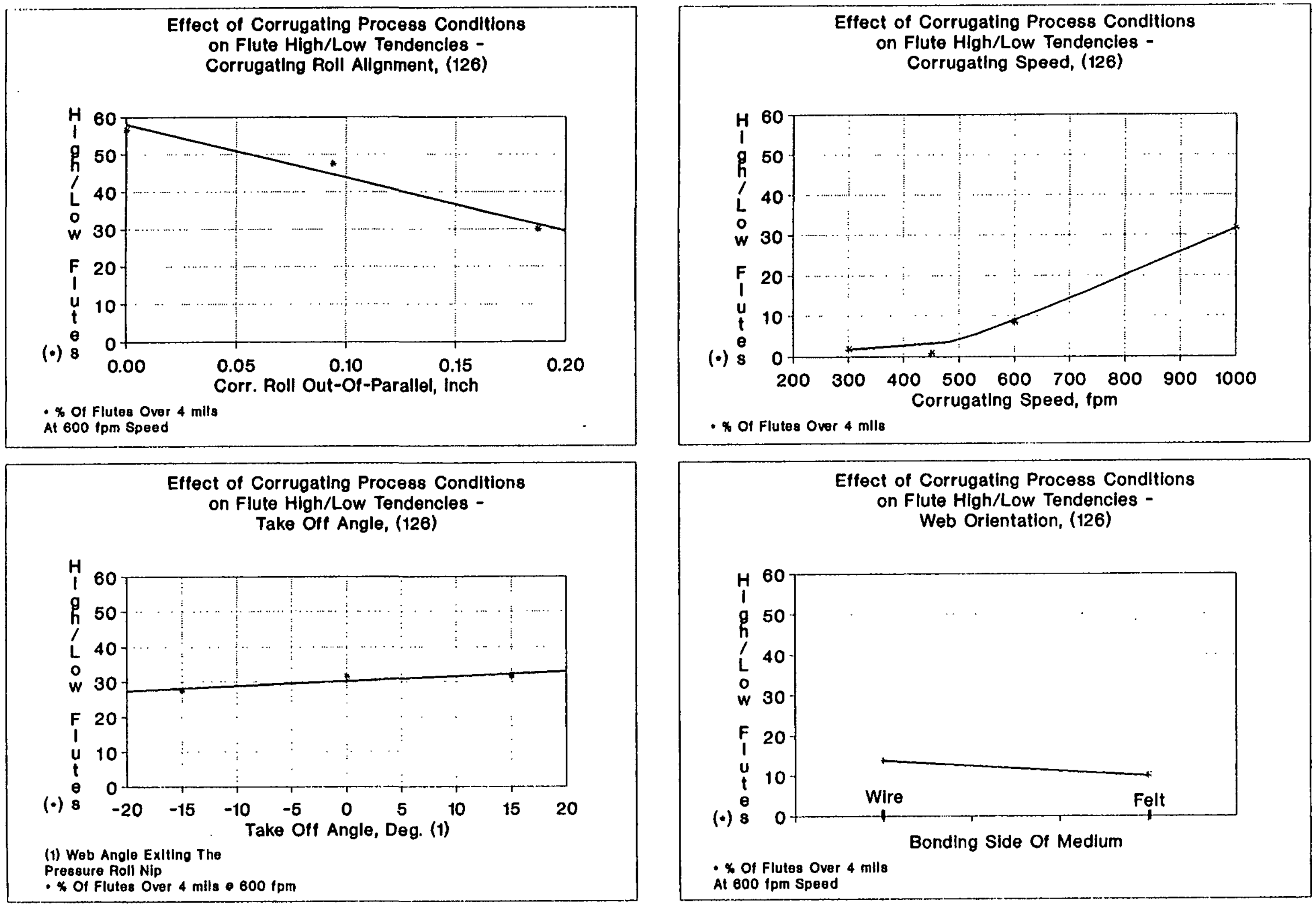


FIGURE 3.5
Effect of Corrugating Variables on High/Low Flute Defect



nishes. Medium basis weight levels of 26 and 33 lb/msf were included. The influence on high/low flutes of medium web tension, medium preconditioning steam, medium preheater wrap, corrugating roll pressure, out-of-parallel corrugating rolls, speed, take-off angle, and medium web orientation was evaluated. All eight process variables had some effect on high/low flutes. The listing of the variables in the order of their impact, greatest to least, and the direction of change in the variable needed to reduce the high/low flute defect were: decreased medium web tensile force, decreased speed, increased corrugating roll pressure, increased use of medium preconditioning steam, a negative take-off angle, and increased medium preheater wrap. Slightly less high/low flutes occurred when the medium was corrugated with the felt side toward the single-facer bond. This is most likely due to a minor difference in a surface property of the medium between the two sides, such as the coefficient of friction. The greater out-of-parallel corrugating roll condition actually reduced high/low flutes. This seems contrary to logic and may only indicate that the "normal" corrugating roll bearing position setting for this particular pilot-size single-facer was really out-of-parallel, (126).

Figure 3.6 summarizes the results of a high/low flute study on a pilot-size single-facer using 26 and 33 lb/msf commercial mediums. The experimental results show that the high/low flute defect is reduced by a slower corrugator speed and a lower basis weight corrugating medium, (17).

Figure 3.7 summarizes the experimental results of a high/low flute study run on a pilot-size single-facer using 21 samples of 26 lb/msf commercial corrugating mediums and A-Flute corrugating rolls. The multiple regression analysis of the data indicates that the high/low flute defect is reduced by a corrugating medium having a lower coefficient of friction (measured against a heated steel surface), a more uniform formation, and a higher alcohol/benzene extractive content, (113). The favorable effect of a more uniform corrugating medium formation on reducing the high/low flute defect is confirmed by other research publications, (17, 66, 69, 115).

Figure 3.8 summarizes the test results obtained for a high/low flute study run on a pilot-size single-facer using commercial corrugating mediums ranging in basis weight from 26 to 40 lb/msf. The data show that the high/low flute defect is reduced by a slower corrugating speed and by a lower corrugating medium basis weight, (25, 26, 27).

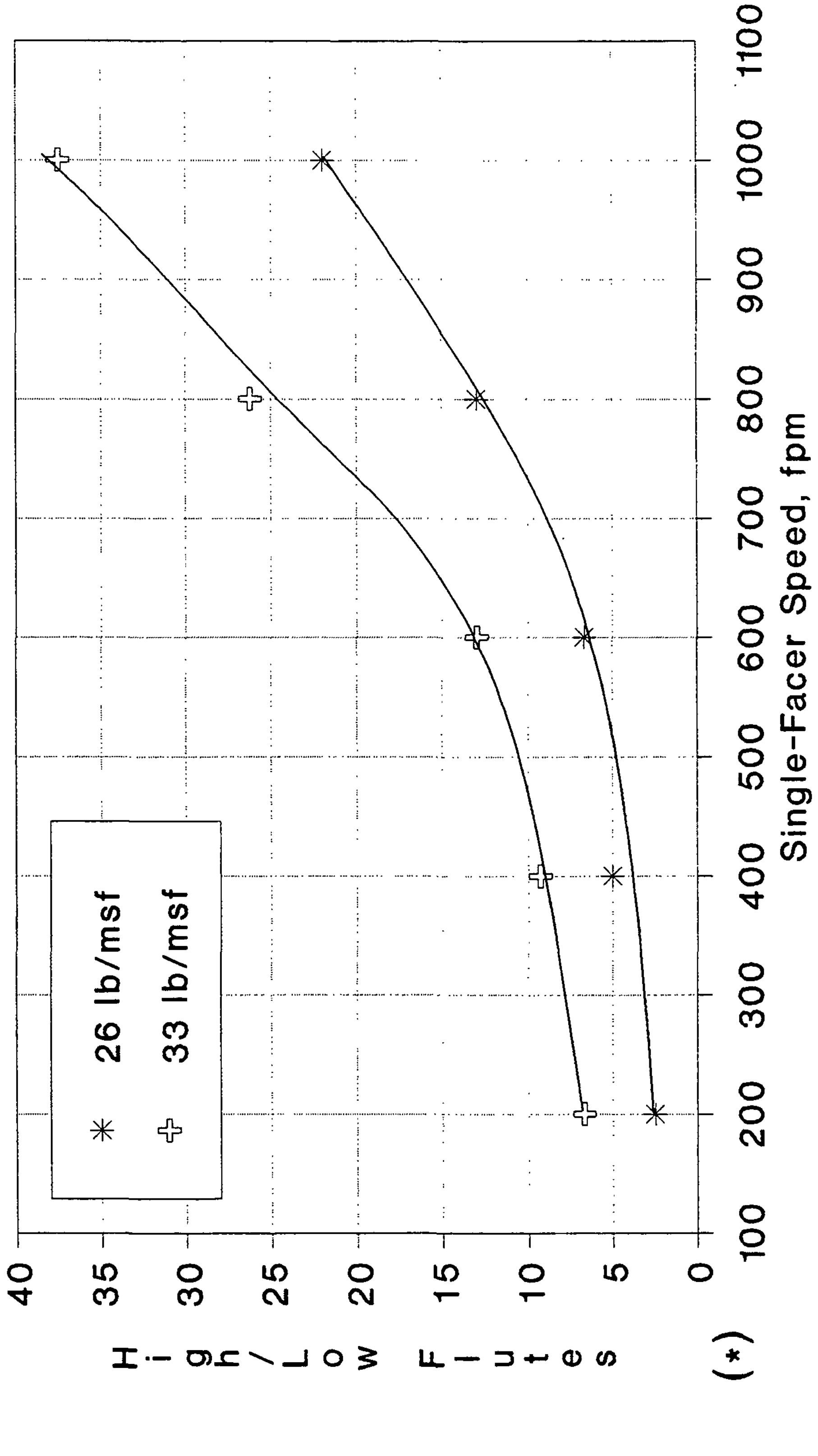
Figure 3.9 summarizes the experimental results of a high/low flute defect study which utilized a laboratory concora tester. The tendency of high/low flutes was characterized by the measurement of the increase in the length of the fluted medium test specimen strip after being corrugated using the concora tester. A greater length increase was taken to represent a material relaxation and dimensional instability that is related to the high/low flute defect. The data show that the high/low flute defect is reduced by a higher corrugating medium moisture content and by a higher corrugating roll temperature, (95).

The major single-facer process variables and corrugating medium material properties that affect the high/low flute defect are summarized in ***Table 3.2.*** It is obvious that some of the listed variables are more reasonable candidates for selection as process control tools for the high/low flute defect than others. For instance, the medium basis weight needs to be based on the issue of cost-effective packaging and not the high/low flute issue. Corrugator speed is another example. It would be illogical to assume that the corrugated industry will move in the direction of reducing corrugator speed in order to minimize the probability of high/low flute formation. However, it is also illogical to assume that the corrugator crew should be allowed to push the machine beyond its designed mechanical speed. To do so would aggravate the mechanical vibrations that produce medium web tension spikes, and would aggravate the bounce of the upper corrugating roll, both of which increase the probability of producing high/low flutes. Increase bounce adversely affects the flute profile definition.

Table 3.2. Major Process & Material Factors Affecting the High/Low Flute Defect

Variable	Direction of Change Needed to Reduce H/L Flutes	References
Medium Web Tension	Decrease	68, 81, 115, 126
Corrugator Speed	Decrease	17, 78, 84, 126
Corrugating Roll Pressure	Increase	68, 78, 81, 84, 115, 126
Corrugating Roll Temperature	Increase	81, 95
Preheater Wrap	Increase	126
Medium Steam Shower	Increase	115, 126
Medium Moisture Content	Increase	81, 95
Medium Basis Weight	Decrease	17, 25, 26, 27, 78, 84
Medium Caliper	Decrease	17
Medium Coef. of Friction Against Heated Steel	Decrease	17, 113
Medium Formation	More Uniform	17, 66, 69, 113, 115
Medium MD Stretch	Increase	17, 25, 26, 27

FIGURE 3.6
Effect of Single-Facer Speed and Medium Basis Weight on High/Low Flutes, (17)



* % of Flutes Over 4 mils.

FIGURE 3.7
Medium Properties Affecting High/Low Flute Defect, (113)

$$H/L = 1.39 + a(A) - b(B) - c(C)$$

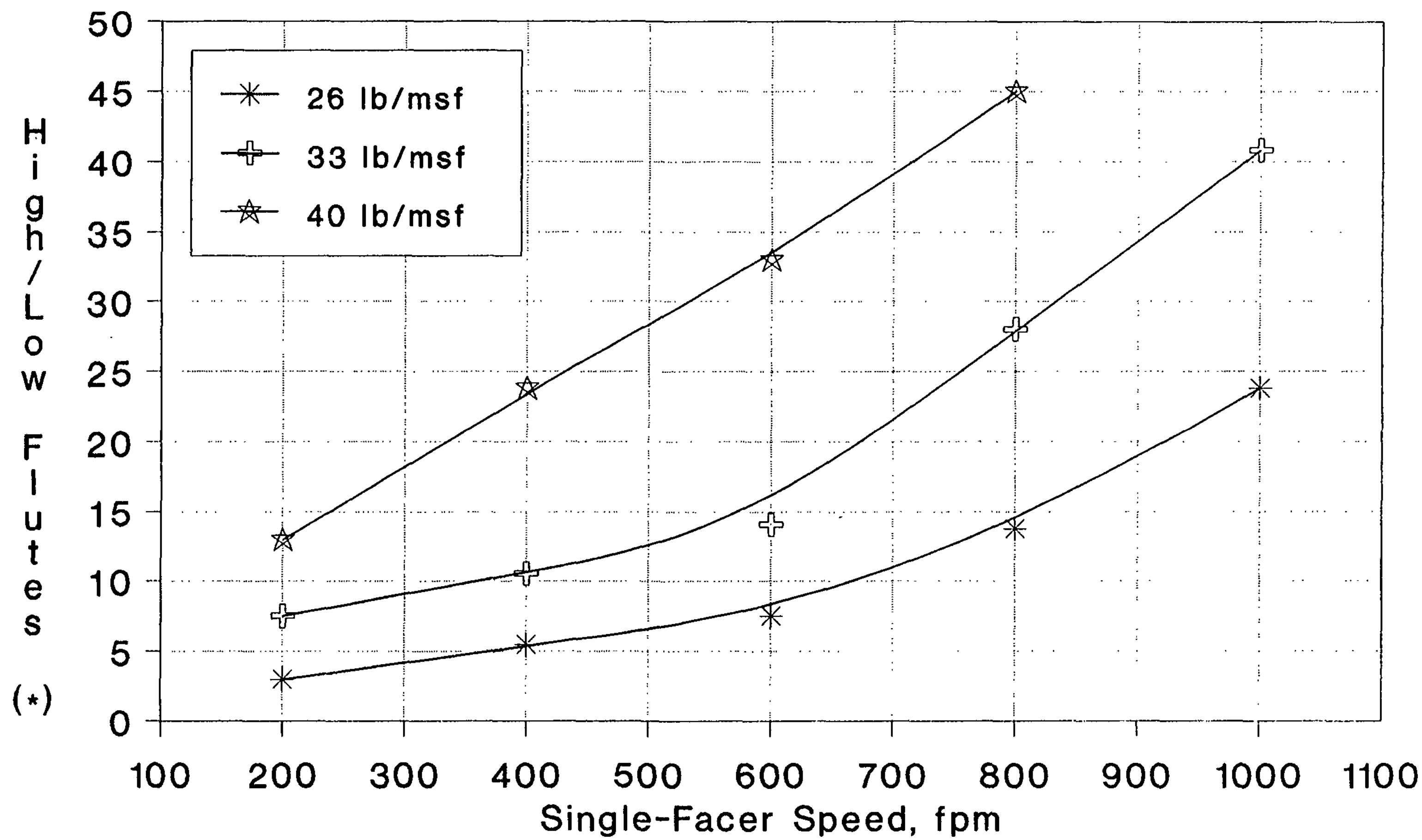
$$r^2 = 0.578$$

a = 6.25
b = 0.38
c = 0.083

A = Coef. of Kinetic Friction
B = Alcohol-Benzene Extraction, %
C = Thwing Formation, units

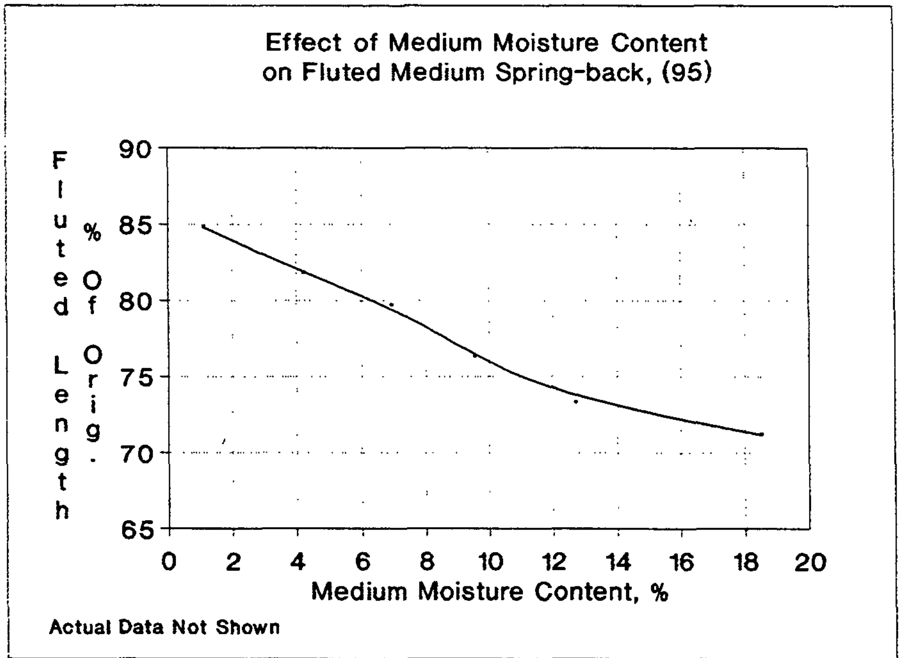
H/L = Average Flute High/Low Difference, mils

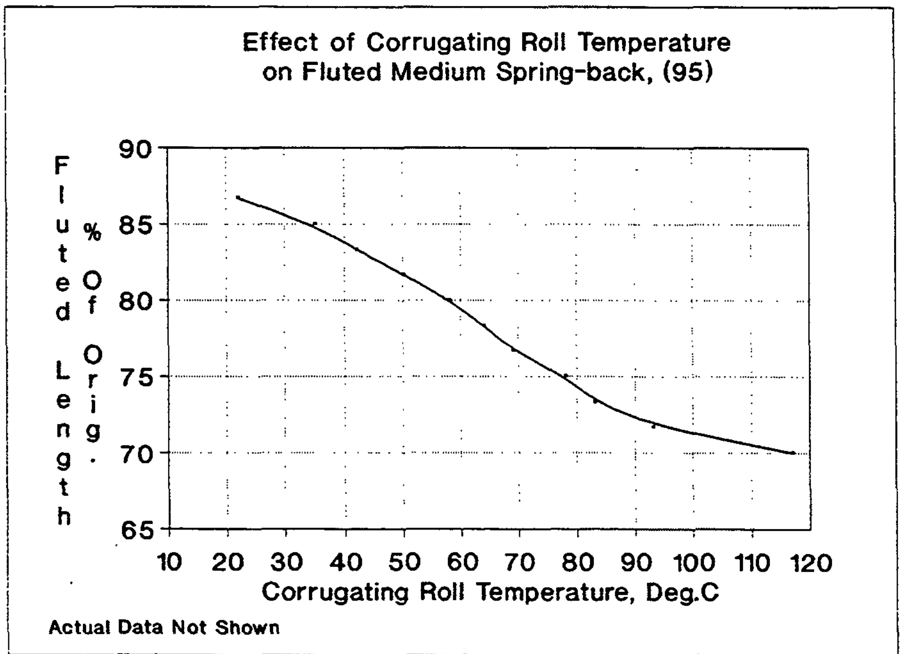
FIGURE 3.8
Effect of Medium Basis Weight on High/Low Flute Defect, (25, 26, 27)



* % of Flutes Over 4 mils.

FIGURE 3.9
Effect of Corrugator Process Variables on Fluted Medium Spring-back





The experimental data are consistent with regard to the beneficial effect of a higher medium moisture content and a higher medium temperature at the point of flute formation. High/low flute defects are reduced by a higher medium rollstock moisture content, by the greater use of medium steam showers, by the greater use of medium preheating, and by higher corrugating roll temperature. It is hypothesized that the higher medium temperature and moisture content decrease the stiffness of the medium and increase its stretch, (25, 26, 27). It is also hypothesized that the higher moisture content reduces the plastic temperature of the medium fibers,(78, 87), and allows the flute forming strains to be dissipated by the MD/ZD shear of the medium, (38). The higher medium moisture content also results in a lower caliper for the fluted medium, (69). This compaction of the fiber as the flute formed may also assist in maintaining the fluted shape.

Medium web tension and medium formation both affect the high/low flute defect. These two effects may help to explain the cross corrugator direction high/low flute pattern that has been observed, (145). Formation and basis weight streaks and a nonuniform cross machine web tension could produce this CD effect.

The coefficient of friction can be reduced on the corrugator by the use of a lubricant applied to the medium web, ***Table 3.3.*** A low molecular weight, low density, nonemulsifiable polyethylene lubricant is the most effective type. It is an inexpensive, solid material which can be applied by having the medium web rub against a bar of the lubricant as it feeds into the singlefacer. A lubricant application rate of 0.0084 lb lubricant per msf medium is sufficient to produce the results shown in ***Table 3.3***, (94, 96).

Table 3.3. Effect of Medium Lubrication on the Coefficient of Friction and High/Low Flutes, (94, 96)

Property	Without Lubricant	With Lubricant
Coefficient of Friction Against Hot Steel	0.23	0.08
High/Low Flutes (% of value without lubricant)	100%	73%

Figure 3.10 shows the effect of pulp refining and paper machine wet pressing on the medium properties of MD tensile, MD tensile stretch, ZD extensional stiffness, and porosity. Both refining and wet pressing serve to increase the density and the fiber bonding of the medium, which increases the tensile strength and the tensile stretch. However, it also produces a less porous sheet which may be less receptive to preconditioning on the corrugator. Refining did not affect the ZD extensional stiffness, but it was increased by wet pressing, (15).

Wet pressing and refining are methods commonly used at mills to improve the compressive strength of medium. These compressive strength improvement techniques, however, may adversely affect the medium properties important to high/low flutes. This point is raised to remind the reader of the observation made in Chapter 1. There are many extraordinary demands placed on corrugating medium, and there is an important need to understand these demands, to compromise these demands (but only when absolutely necessary), and to control the papermaking and corrugating processes so as to achieve the best total corrugated board product.

In summary and with consideration of only the issue of high/low flutes, the total body of technical information available indicates that the medium mills and the box plants should consider the feasibility of the following actions to reduce the probability of encountering the high/low flute defect.

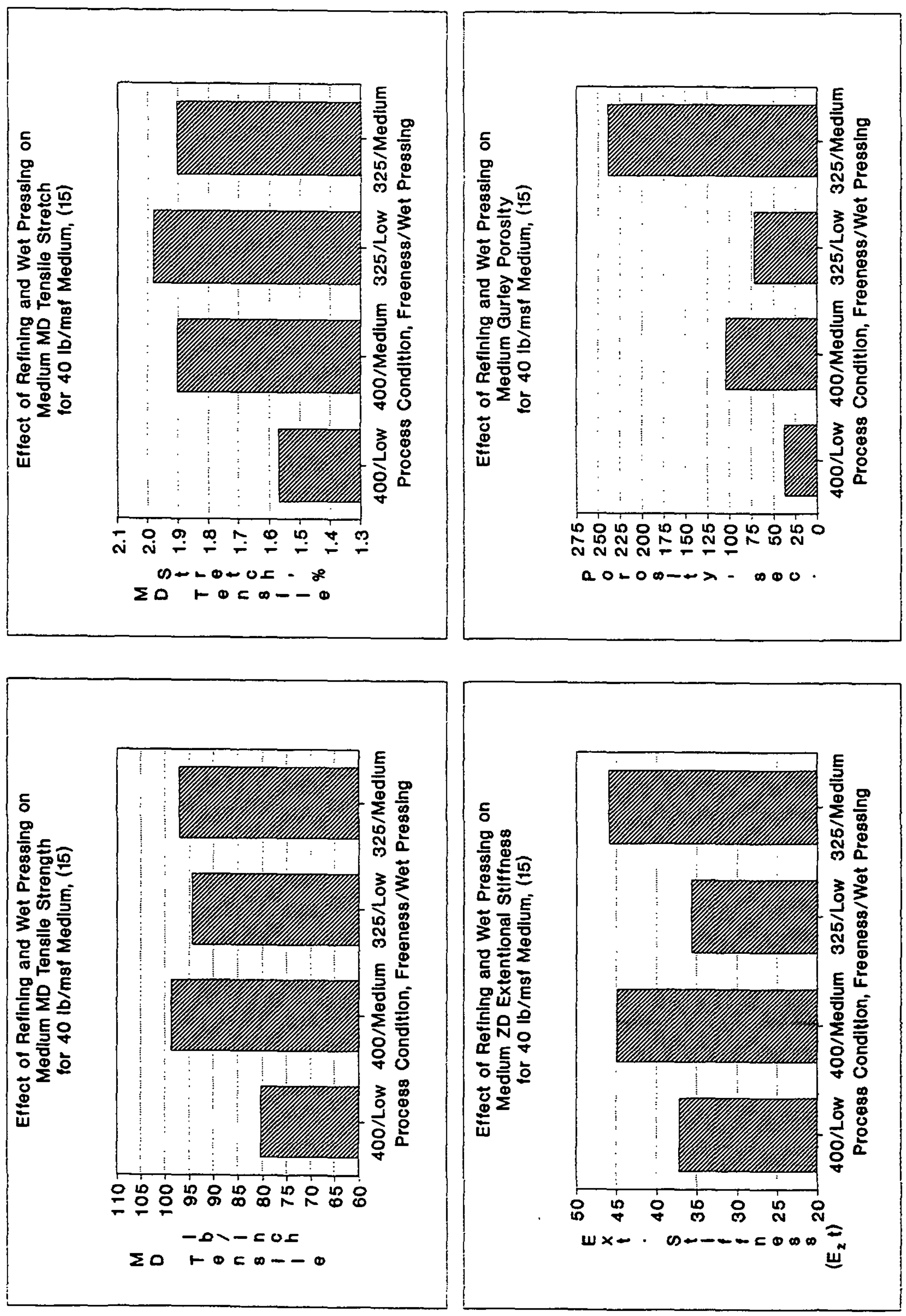
The medium mills should consider:

* Increase MD Stretch.
* Improve Formation.
* Increase Moisture Content.
* Reduce Hot Coefficient of Friction.
* Reduce Caliper.

The box plants should consider:

* Reduce Medium Web Tension.
* Increase Medium Steam Preconditioning.
* Increase Medium Preheating.
* Increase Corrugating Roll Pressure.
* Increase Corrugating Roll Temperature.
* Unlock Preheater Drums.
* Properly Maintain Mechanical Equipment to Minimize Vibration and Friction Forces.
* Properly Maintain Steam System to Raise Medium Temperature and Moisture Content.

FIGURE 3.10
Effect of Paper Mill Refining and Wet Pressing on Medium Properties



Chapter 4

Fractured Flutes

The term "Fractured Flutes" refers to the physical separation of the corrugating medium fiber network during the flute forming process in the single-facer. Material engineering theory describes two possible types of separation that might be expected. One separation type is that due to forces acting in the in-plane machine direction of the medium, and the other separation type is due to a shear force acting in the machine direction/thickness (caliper) direction of the medium. The in-plane type of failure in paper is usually associated with a tensile or tear type of force. The shear force type of failure in paper is usually associated with a bending force that causes delamination. Both tensile and bending forces exist in the flute forming process, (24, 126, 129, 154). It may seem that the bending of the medium occurs only to the medium material located at the tips of the final flute. This is not correct. The bending force is applied to the total surface area of the medium web as the medium is drawn into the corrugating roll labyrinth, (46).

Examination of medium fractured during flute forming in commercial corrugating operations indicates that the failure is an in-plane separation, specifically a MD tensile failure. Shear deformation forces are at work during the bending of the medium to form the flute shape. The main contribution of shear is to help dissipate some of the tensile strain, (24, 126, 129, 154). The only time that the author has observed shear fracture failure of the medium after corrugating was when a prelaminated two-ply medium was used. The medium separated at the lamination glue line and produced two single-faced corrugated sheets rather than one single-wall sheet.

The severity of the flute fracture defect can vary widely. In the worst case, the medium is literally shredded. Pieces of medium fall out of the web, and it is generally impossible to feed the single-faced web through the double backer. Flute fracture failure is often difficult to detect by eye at the point where it first starts to occur. The fracture failure lines propagate in the cross machine direction and are generally not longer than 1/4 inch. Fracture failure generally occurs in the flute sidewall areas, although the fractures can occur at the flute tips in heavy basis weight medium, (46). A method for testing for fracture was not found in the literature. A simple method, used by the author, is the "Thumb Nail Test." It consists of rapidly rubbing the thumb nail over the flutes of a single-faced sample, one time. The rubbing should be in the machine direction and should be done using very little pressure. The thumb nail force will cause the fractured area to separate and make the fracture more visible. Looking at the sample over a light box accentuates the failure lines. For those with delicate hands, the rounded end of a utility knife handle can be used in place of the thumb.

It was pointed out in Chapter 1 that the fluted medium is the heart of the corrugated board structure and that the quality of the corrugated board is determined at the single-facer, (7, 129). ***Figure 4.1*** shows the effect of fractured flutes on the combined board flat crush strength and on the fluted medium edge crush strength. The degree of fracture represented by the data in ***Figure 4.1*** is the least possible. It represents the point where fracture has just begun to occur in the medium. Flat crush is reduced by 9.7%, and the medium edge crush strength is reduced by 14.7%, (129). On average, the medium contributes about one-third of the total combined board Edge Crush Test. Based on this ratio and on the McKee box compression model, the 14.7% reduction in the medium fluted edge crush would result in an estimated 3.6% loss in box compression. The author believes that the actual reduction in box compression would be considerably greater than 3.6% since the combined board flexural stiffness would also be adversely affected by the flute fracture. It is the strong opinion of the author that no amount of flute fracture is tolerable. Any degree of fracture makes the board commercially unacceptable.

Figure 4.2 shows the effect of medium web tension and flute size on flute fracture. The experiments were conducted on a pilot-size single-facer using a commercial medium. The data show that a higher me-

FIGURE 4.1
Effect of Fractured Flute Defect on Corrugated Board Properties

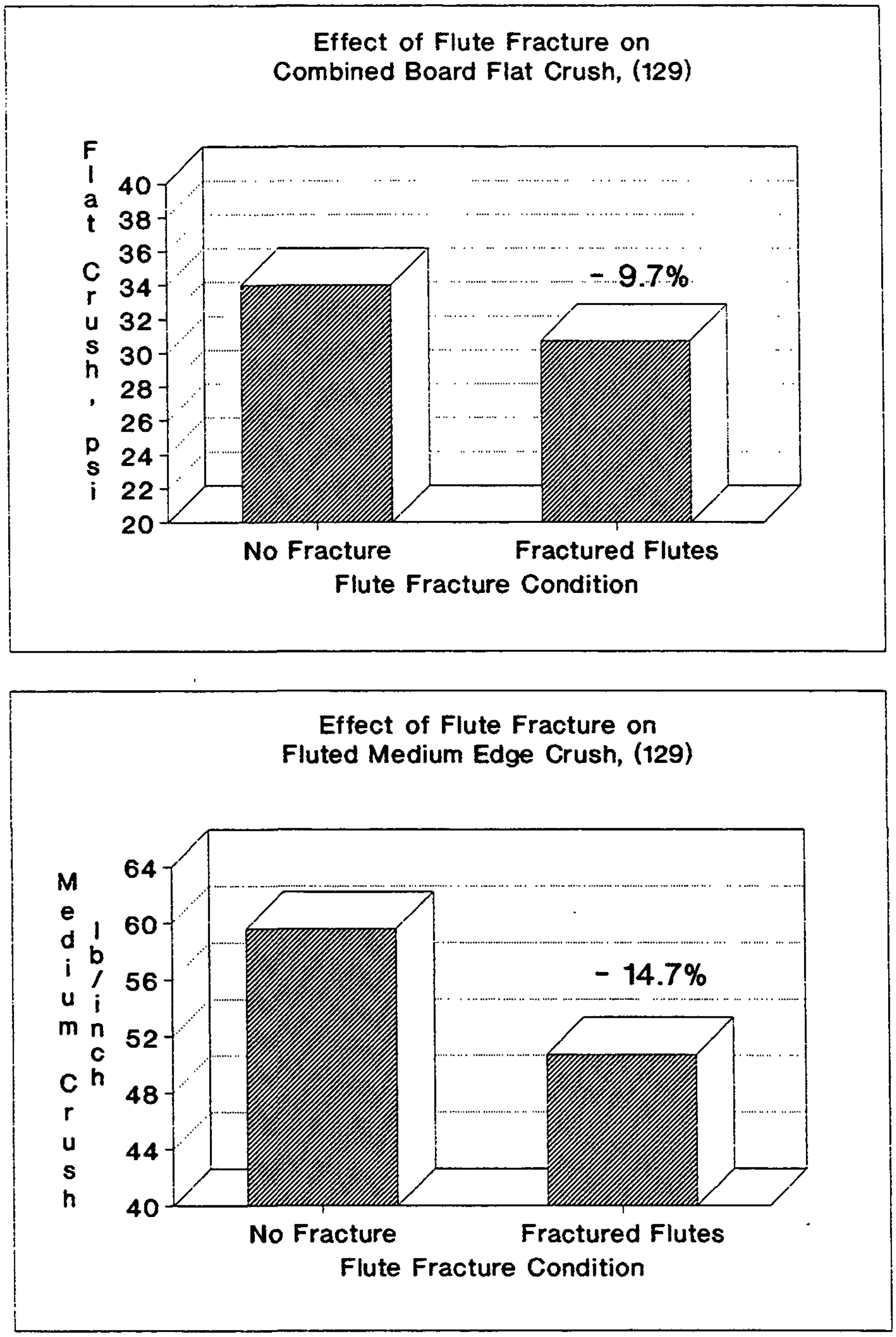
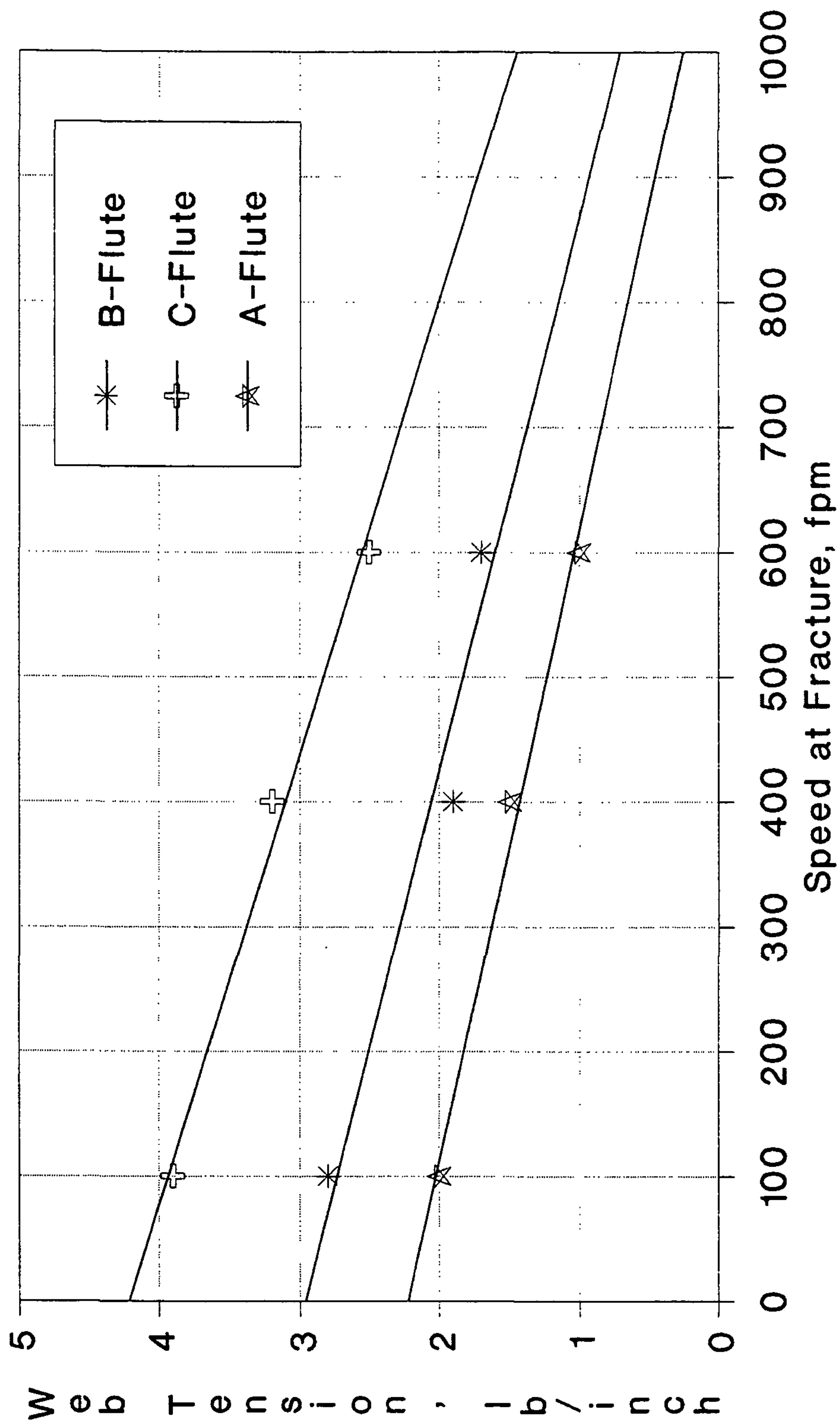


FIGURE 4.2

Effect of Medium Tension on Flute Fracture Speed, (24)



dium web tension produces flute fracture at slower corrugator speeds. At a given medium web tension, A-Flute fractured at a slower speed than B-flute, and B-Flute fractured at a slower speed than C-Flute, (24). The fact that fracture speed does not correlate with flute height suggests that the design of the flute profiles (radii, angles, and clearances) and/or the surface characteristics of the corrugating rolls are more controlling than flute height.

Figure 4.3 and ***Figure 4.4*** summarize the results of a flute fracture study conducted on a pilot-size single-facer using several commercial mediums. The corrugating medium materials evaluated in the experiment included semichemical, kraft, and recycled fiber furnishes. Medium basis weight levels of 26 and 33 lb/msf were included. The effect on flute fracture of the variables of medium web tension, medium preconditioning steam, medium preheater wrap, out-of-parallel corrugating rolls, speed, take-off angle, and medium web orientation was evaluated. The listing of the variables that affect fracture in the order of their impact, greatest to least, and the direction of change in the variable needed to reduce the probability of flute fracture were: decreased web tension, increased medium preconditioning steam, and increased medium preheater wrap. The corrugating roll pressure, out-of-parallel corrugating rolls, and take-off angle had little or no effect on flute fracture. The effect of the medium moisture content indicates an optimum operating plateau region of 6% to 12%. Medium moisture content levels below 6% and above 12% resulted in increased fracture tendencies. The web orientation effect (wire side or felt side toward the single-face bond) is most likely due to differences in surface properties, (126).

Figure 4.5 summarizes the results of a study to determine the effect of medium physical properties on flute fracture. The experiments were done on a pilot-size single-facer using medium produced on a pilot-size paper machine. A full factorial experimental design was used. The fracture tendency in this study is defined as the highest medium web tension attained at a corrugator speed of 600 fpm without producing fractured flutes. The multiple regression equation developed from the experimental data includes interactive terms, such as the interaction of the CD elastic modulus and the CD tensile stretch. (Note: It seems more logical to the author that the MD elastic modulus and MD stretch would be related to fracture. There is a possibility that the CD effects described in the reference are typographical errors.) The interactive terms make it very difficult to quantify the relative importance of the individual variables. However, it can be inferred that a medium that is less porous, that has a lower CD elastic modulus and CD stretch, and which has a more uniform formation would be beneficial to reducing the flute fracturing tendency, (92, 93).

Figure 4.6 is an equation for predicting the fracture speed of a medium based on the corrugating process variables of roll-stand brake tension, radii of curvature of the flute tips on the corrugating roll and the effective wrap angle of the medium web in the corrugating roll labyrinth, and on the medium properties of MD tensile strength, MD stretch, soft platen caliper, and coefficient of friction against a heated steel surface. The model indicates that the flute fracturing tendency is decreased by reducing the roll-stand brake force (lower web tension) and by a medium having a higher MD tensile strength, a higher MD stretch, a lower caliper, and a lower hot coefficient of friction. The predicted fracture speed based on the model is compared to experimental flute fracture data obtained for three different commercial mediums using a pilot-size single-facer. The comparison is shown in ***Figure 4.7*** and it indicates that the model is reasonably accurate and is a good predictive tool, (26, 26, 27).

The major single-facer process variables and the major medium material properties that affect flute fracture are summarized in ***Table 4.1.*** As was discussed in Chapter 3, slowing the corrugator speed is not suggested as a long-term strategy for the control of flute fracture. On the other hand, it is also not suggested that the corrugator speed be increased beyond the mechanical design limit of the specific corrugator. Doing so will increase the mechanical vibrations and result in medium web tension spikes that can cause fracture. The excessive speed will also cause bounce in the upper corrugating roll and poor flute forming, (98, 149).

Table 4.1. Major Process & Material Factors Affecting The Flute Fracture Defect

Variable	Direction of Change Needed to Reduce Flute Fracture	References
Medium Web Tension	Decrease	24, 25, 26, 27, 126
Corrugator Speed	Decrease	24, 126
Roll-Stand Brake	Decrease	25, 26, 27
Medium Preheater Wrap	Increase	126
Medium Temperature	Increase	38, 78, 84
Medium Steam Shower	Increase	126
Medium Moisture Content	Increase	38, 78, 84, 126
Medium MD Tensile	Increase	25, 26, 27, 46
Medium MD Stretch	Increase	25, 26, 27, 46
Medium Caliper	Decrease	25, 26, 27
Medium Coef. of Friction Against Heated Steel	Decrease	25, 26, 27, 46, 78, 129, 134
Medium Formation	More Uniform	92, 93
Shives in Medium	Decrease	110, 114
Medium Porosity	Decrease (Less Porous)	92, 93

FIGURE 4.3
Effect of Corrugator Process Variables on Flute Fracture Defect

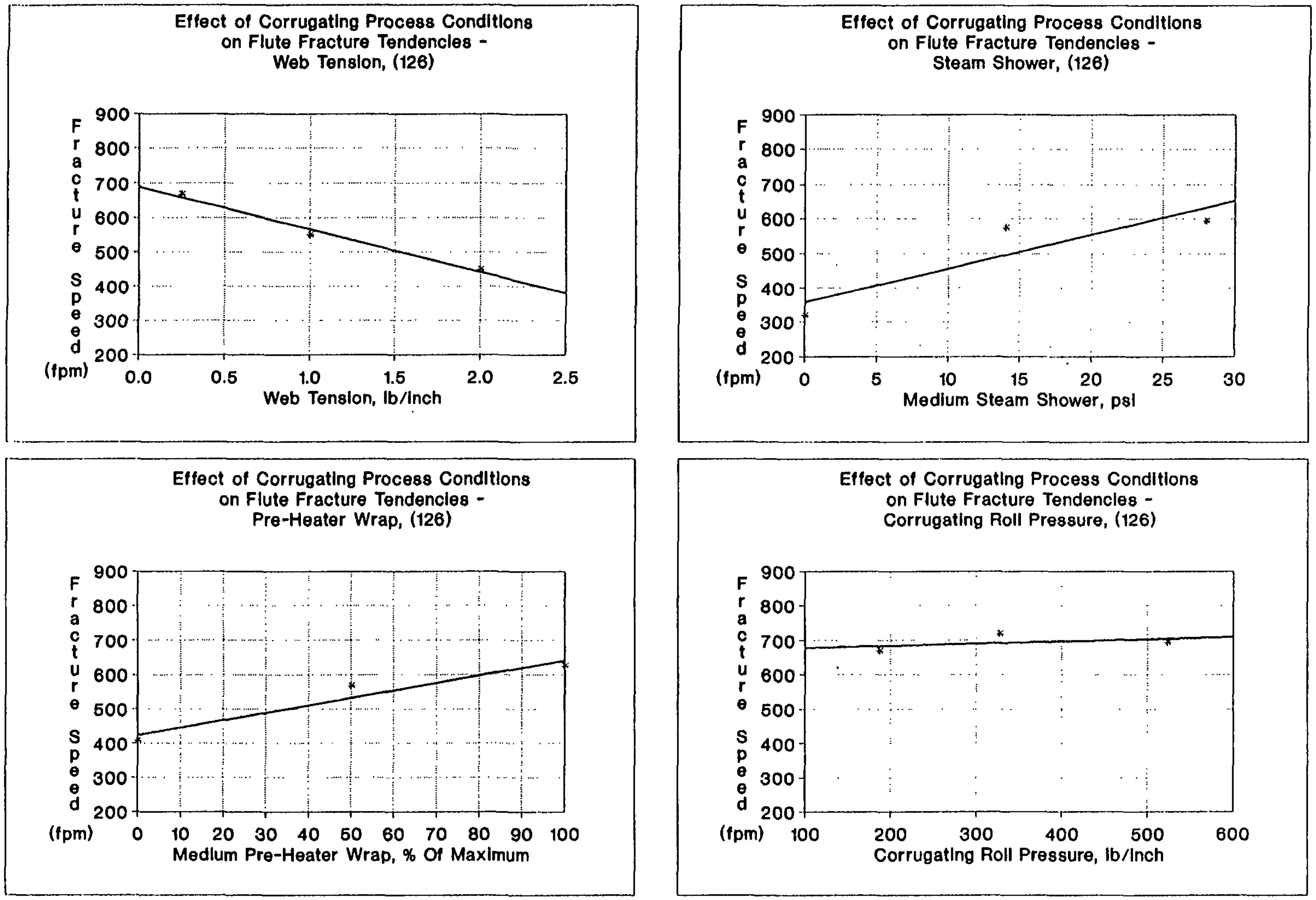


FIGURE 4.4
Effect of Corrugator Process Variables on Flute Fracture Defect

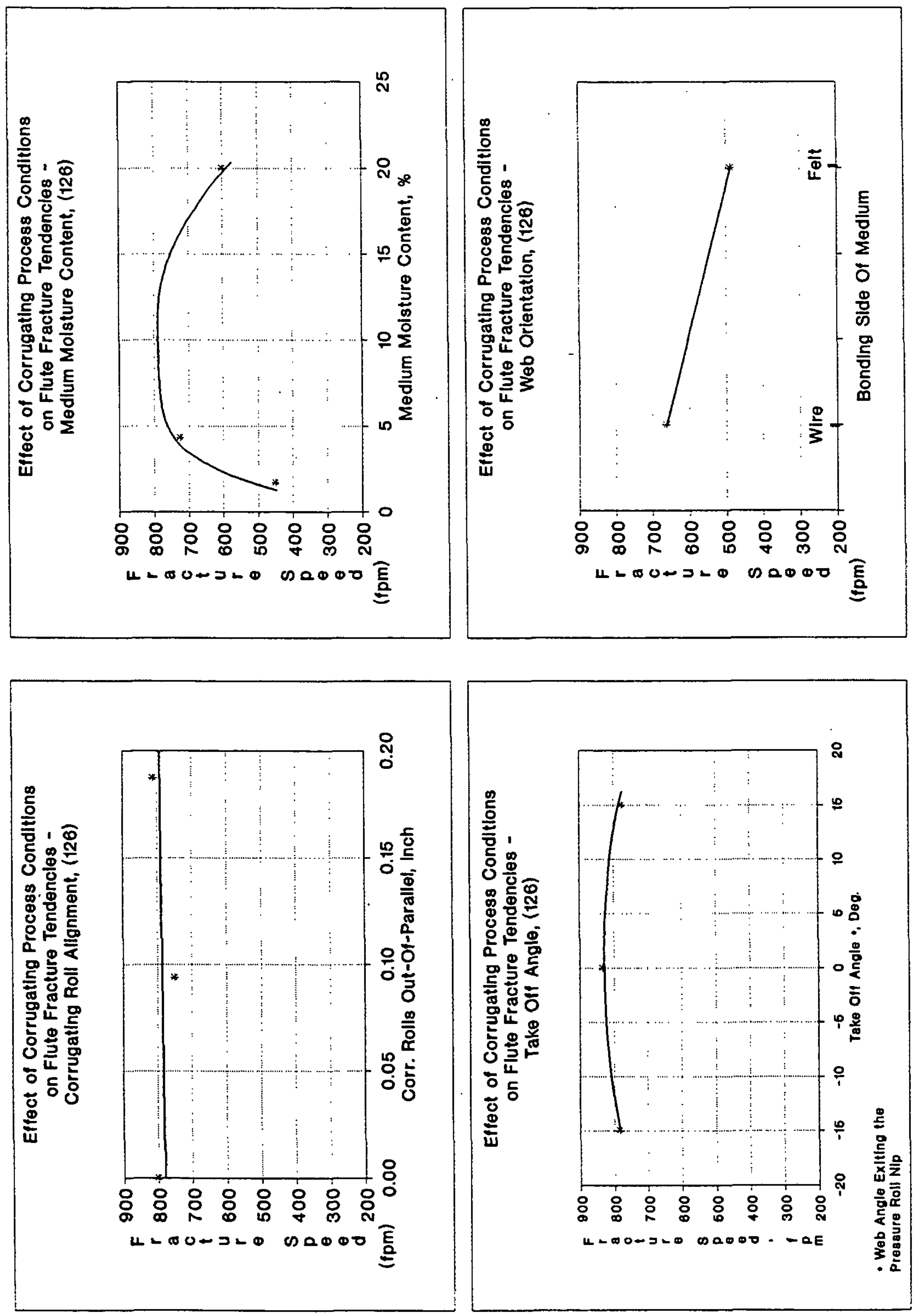


FIGURE 4.5

Effect of Medium Properties on Flute Fracture, (92, 93)

$$\text{Fract.} = a(A) - b(B) - c(C) - d(D) + e(E) - f(F) + g(G) + 12.79$$

$$r^2 = 0.76$$

Fract. = Lowest Web Tension Causing Fracture @ 600 fpm

a = 0.0440	A = Air Resistance, sec.
b = 0.0275	B = CD Mod. of Elast., $\frac{psi}{1000}$
c = 2.458	C = CD Stretch, %
d = 0.0853	D = Formation, units
e = 0.00628	E = B times C
f = 0.1657	F = A times C
g = 0.000023	G = A times B times C

FIGURE 4.6

Medium Fracture Speed Model, (25, 26, 27)

$$FS = \left(\frac{297}{e^{\mu\theta}}\right)\left(T_f - \frac{4.895\,T_f\,t}{(R + t/2)\epsilon} - T_o e^{\mu\theta}\right)$$

FS = Fracture Speed, fpm

T_f = MD Tensile Strength, lb/inch

t = Soft Platen Caliper, inch

μ = Coef. Hot Friction, Steel surface

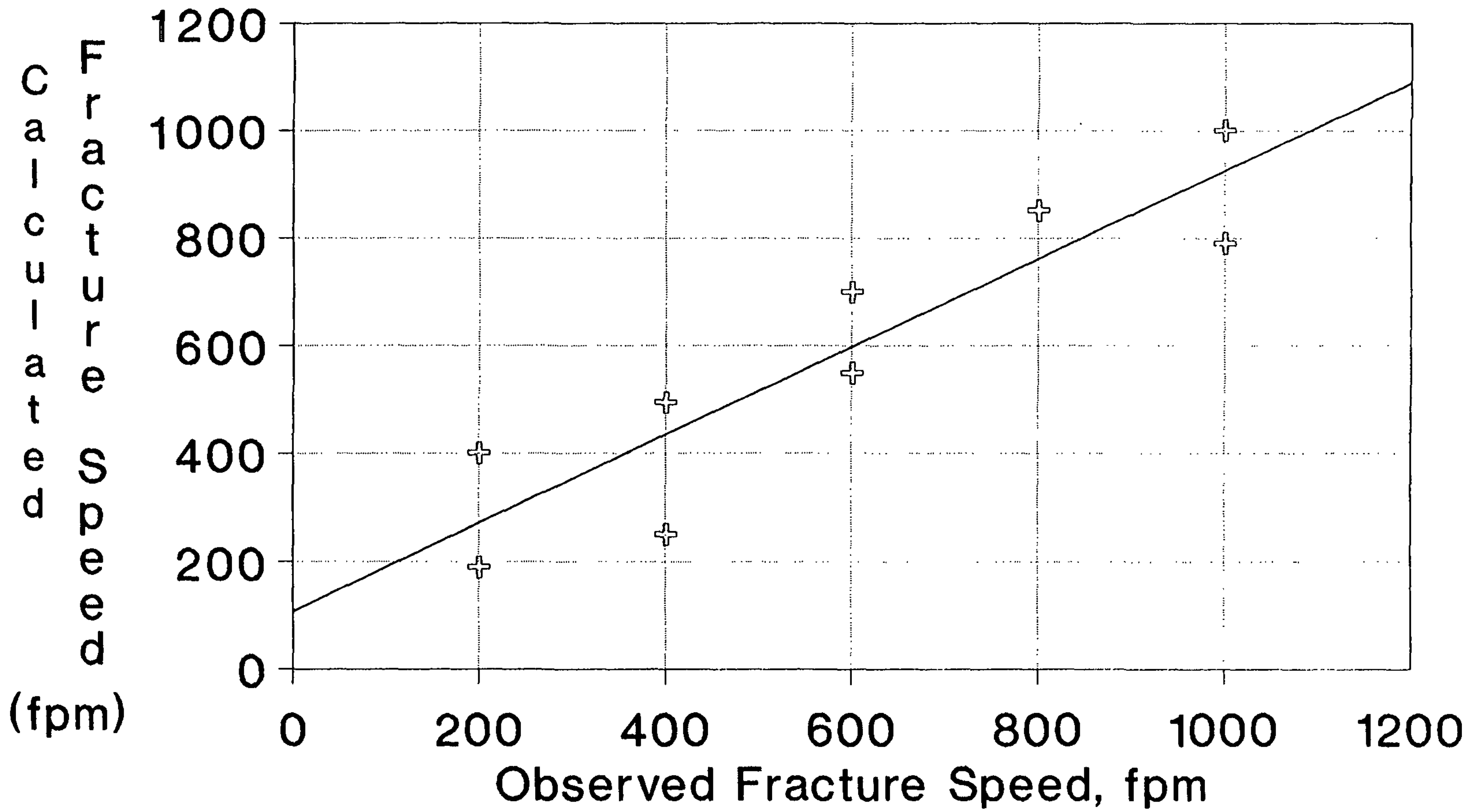
θ = Effective Wrap Angle In Labyrinth, radians

T_o = Brake Tension, lb/inch

ϵ = MD Stretch, %

R = Radius of Curvature of Flute Tip

FIGURE 4.7
Validation of the
Flute Fracture Model, (25, 26, 27)



See FIGURE 4.6 for the Model.

Fracture occurs when the tensile stress and the tensile strain in the medium web due to flute formation bending forces, frictional forces, and roll-stand brake forces exceed the tensile strength and tensile stretch of the medium in the corrugating roll labyrinth, (24, 25, 26, 27, 38, 78, 84, 129, 154). The beneficial effect of a higher medium MD tensile strength and stretch is due to the ability of the material to withstand greater corrugating stresses and strains before failing. Reducing the roll-stand braking force and using a corrugating medium with a lower hot coefficient of friction both reduce the fracture tendency by reducing the medium web tension. A more uniform formation in the medium and a reduction in the occurrence of shives in the medium both reduce the probability of localized tension spikes. A shive is a bundle of fibers or a small piece of underpulped wood. A lower caliper medium is beneficial to reducing fracture because it increases the relative clearances of the medium in the sidewall area of the corrugating roll teeth.

The probability of flute fracture is reduced when the medium web entering the corrugating roll flute forming labyrinth has a higher moisture content and a higher temperature. The higher moisture content and temperature "soften" the web by reducing its stiffness, increasing its MD stretch at tensile failure, and reducing the out-of-plane shear modulus. These are favorable changes. The higher web moisture content also increases the medium's hot coefficient of friction and reduces its tensile strength. These are unfavorable changes. The combined data from the literature indicate that, on balance, the favorable effects out weigh the unfavorable effects, (38, 46).

Two box plant process methods have been invented to reduce the probability of flute fracture, particularly at high corrugator speeds. The first method consists of using a lubricant applied to the medium web as it feeds into the single-facer. The lubricant serves to reduce the friction during the actual flute forming process, (78, 84, 94, 96, 147). It is important that the lubricant selected does not impair the porosity or absorbency of the medium since bonding may be affected, (78, 84). A low molecular weight, low density, non-emulsifiable polyethylene lubricant is the most effective type. It is an inexpensive, solid material that can be applied by having the medium web rub against a bar of the lubricant. A lubricant application rate of 0.0084 lb lubricant per msf medium is sufficient to produce the results shown in ***Table 4.2***, (94, 96).

The second method for reducing and controlling the medium tension consists of medium web in-feed rolls located close to the corrugating rolls. The in-feed rolls act as a web tension buffer against the upstream sources of tension. The device was shown to be very effective in increasing the corrugator speed at which flute fracture occurs on a pilot-size single-facer, ***Figure 4.8.*** (146).

Table 4.2. Effect of Medium Lubrication on the Coefficient of Friction and Fractured Flutes, (94, 96)

Property	Without Lubricant	With Lubricant
Coefficient of Friction Against Heated Steel	0.23	0.08
Maximum Corrugator Speed Without Fractured Flutes	550	+1000

In summary and with consideration of only the issue of flute fracture, the total body of technical information available indicates that the medium mills and the box plants should consider the feasibility of the following actions to reduce the probability of encountering the flute fracture defect.

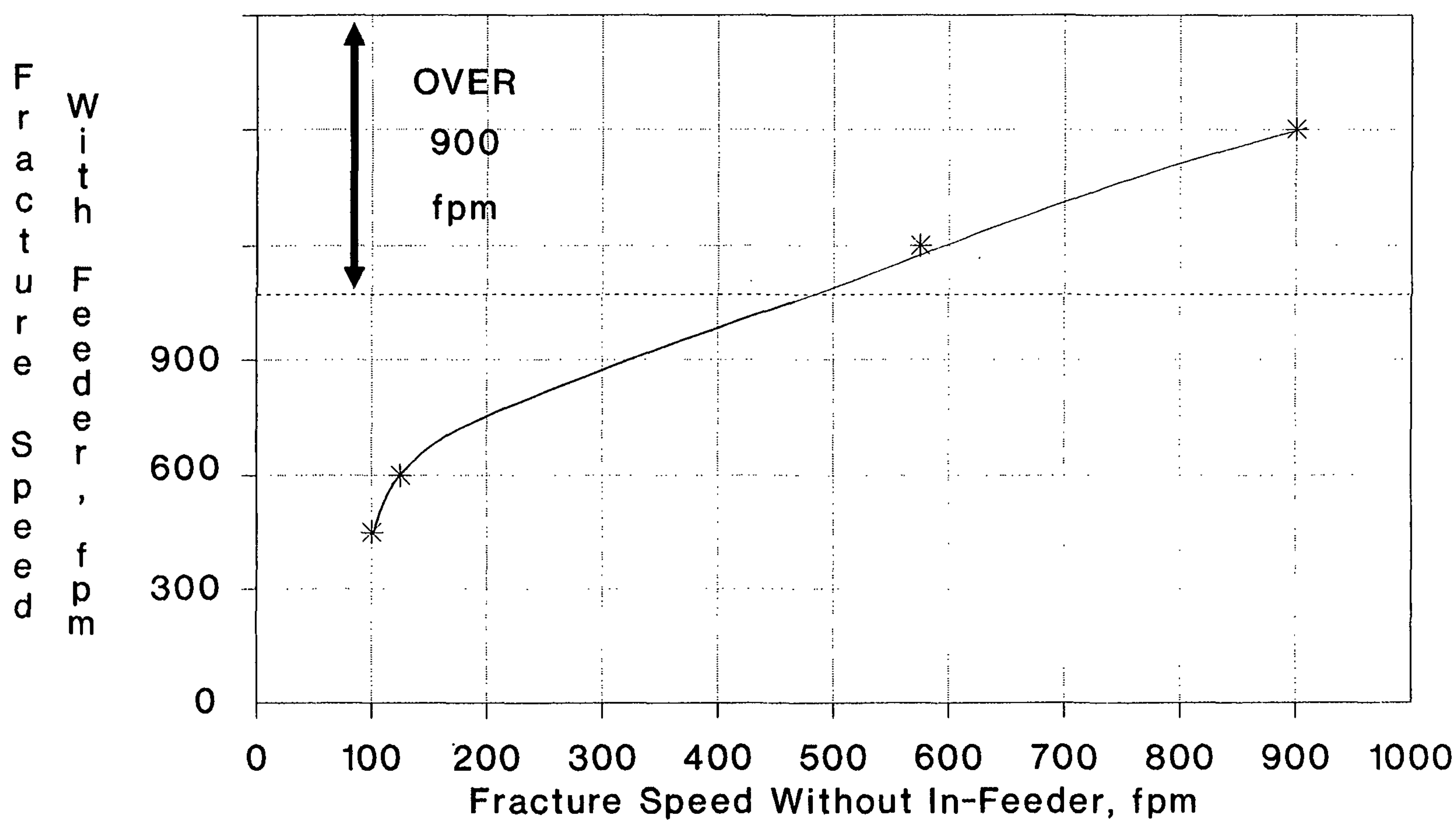
The Medium Mills should consider:

* Increasing MD Tensile Strength.
* Increasing MD Stretch.
* Improve Formation.
* Reduce Shive Count.
* Increase Moisture Content.
* Reduce Hot Coefficient of Friction.
* Reduce Caliper.

The Box Plants should consider:

* Increase Medium Preheating.
* Increase Medium Steam Preconditioning.
* Increase Corrugating Roll Temperature.
* Reduce Medium Web Tension.
* Unlock Preheater Drums.
* Properly Maintain Mechanical Equipment to Minimize Vibration and Friction Forces.
* Properly Maintain Steam System to Raise Medium Temperature and Moisture Content.

FIGURE 4.8
Effect of Medium In-Feed Rolls on Flute Fracture Defect, (146)



Chapter 5

Medium Strength Loss By Fluting

It is the ultimate desire of package designers and packaging engineers to be able to accurately predict the field performance of corrugated packages based solely on the measured physical properties of the linerboard and medium rollstock used to make the box, and from the size and design of the package. It is the opinion of the author that those designers and engineers who believe that they can now do so with a great degree of accuracy are very much mistaken.

As this chapter will show, it is currently very difficult to predict just the combined board strength properties, which are dependent on the fluted medium, solely from the strength of the starting medium and the flute size, except as an overall average effect. There are too many corrugating process factors that affect the relationship.

The corrugated medium in the combined board is exposed to many different stresses and strains between the single-facer medium roll-stand and the exit side of the single-facer pressure roll nip. The medium web's temperature and moisture content are altered by the preheater drum and the preconditioning steam shower. The medium web is exposed to MD tensile forces from the roll-stand braking system and the various sources of mechanical friction. The greatest effect, however, is in the actual flute forming part of the process.

The medium web is heated by the corrugating rolls, and then stretched and bent to form the flute shape in the corrugating roll labyrinth. Once the flute is formed, it is than squeezed and compressed in the tip and sidewall areas as it reaches the tangent point between the upper and lower corrugating rolls.

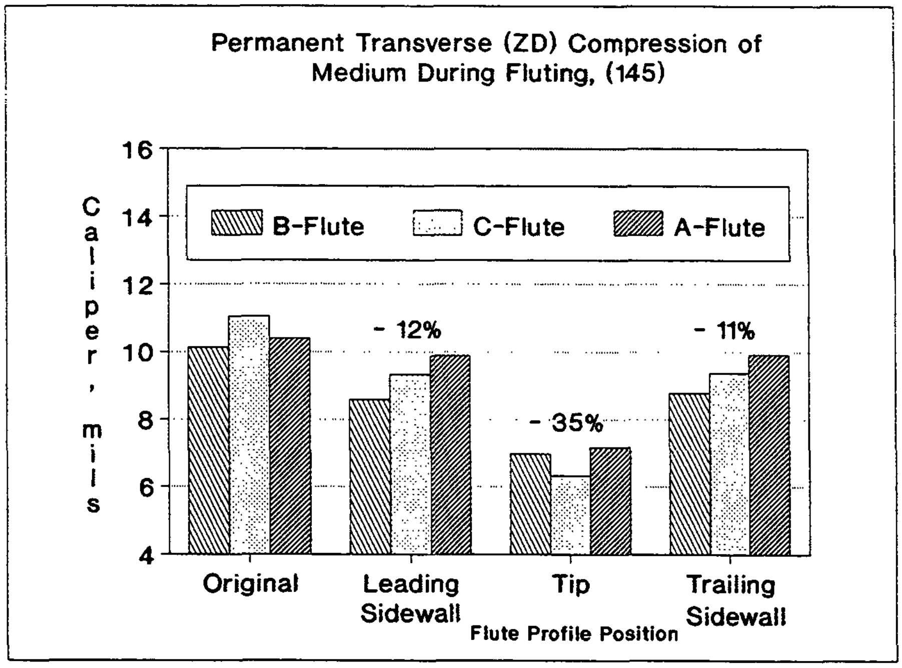
Figure 5.1 shows that the medium is permanently compressed, on average, by 37% in the flute tip area and by 11% in the flute sidewall area, (145, 149). This compression may actually help to reestablish the fiber-to-fiber bonding that was disturbed by the flute forming stresses, (30, 95). Approximately 15% water, by weight, is then added to the medium by the application of the starch adhesive slurry, and the medium flute tip is again compressed in the pressure roll nip. In more technical terms, the medium is exposed to in-plane tensile strain, bending shear strain, and out-of-plane transverse compression strain, (25, 26, 27, 30, 38, 129, 154). As stated in Chapter 1, "the life of the corrugating medium is not an easy one."

The medium plays several key roles in the structural performance of the corrugated board and the corrugated package. Based on the information available in the references, the discussions in this chapter will be mainly limited to the properties associated with the combined board flat crush and edge crush strengths. The flat crush strength of the corrugated board is important to the panel bulge resistance, the compressive strength, and the cushioning characteristics of the corrugated package. The effect of flat crush on panel bulge and the box compression is through the flexural stiffness strength. The medium must be able to maintain the structural integrity of the corrugated board by keeping the linerboard facing as far apart as possible. The edge crush strength of the corrugated board is important to the compressive strength of the corrugated package.

Table 5.1 demonstrates the effect of heat treatment on the physical properties of corrugating medium. The medium was heated for 2 seconds at a temperature of 300 deg.F. The samples were then conditioned at 73 deg.F. and 50% RH before testing. The 2-second treatment time corresponds to a linear contact distance of 8.3 feet for a medium web travelling at 1000 fpm. The treatment conditions are, therefore, representative of the medium preheating that occurs in a commercial single-facer operation.

The data show that the heat treatment produces a 14% increase in the medium material CMT (flat crush effect), a 10% increase in CD ring crush (edge crush effect), a 14% increase in MD tensile strength, a 6% increase in stretch, and an 18% increase in tensile energy adsorption. The MD fold resistance is the only tested property that exhibited a reduction, (75). This shows that the properties of the medium web entering the corrugating rolls are significantly different from the properties of the medium web at the roll-stand.

FIGURE 5.1
Permanent Thickness Compression of Medium During Fluting



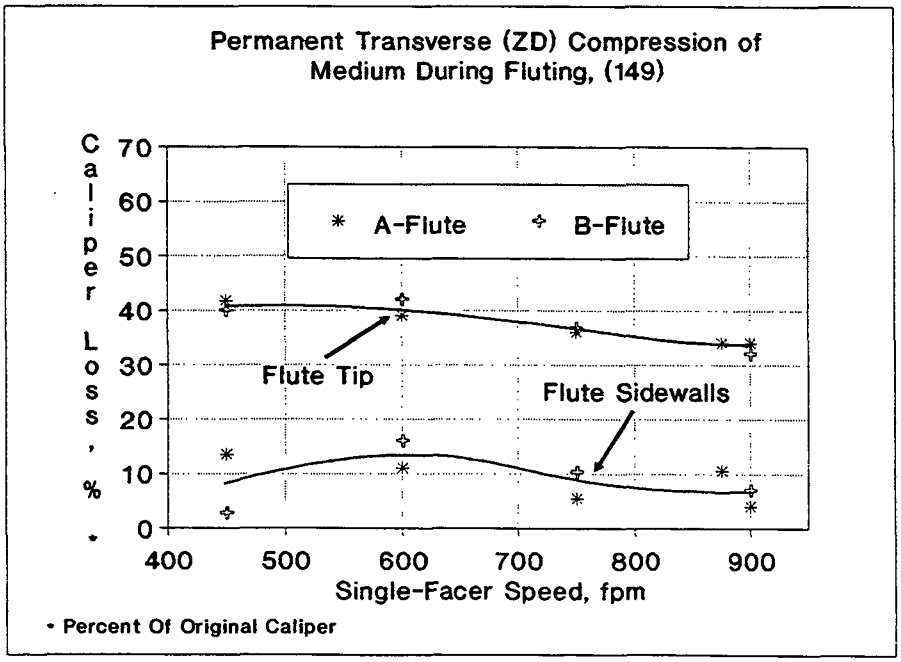


Table 5.1. The Effect of Heat Treatment on Medium Properties, (75) (2-second Treatment at 300 deg.F)

Property	Untreated Value	Treated Value	% Change
Concora Medium Test, N	240	275	+ 14%
CD Ring Crush, kN/m	0.88	0.97	+ 10%
MD Tensile, kN/m	8.7	9.9	+ 14%
MD Tensile Failure Stretch, %	1.7	1.7	+ 6%
Tensile Energy Adsorption, J/sq.m	89	105	+ 18%
MD Fold Endurance, no. folds	100	43	- 57%

Figure 5.2 shows the effect of the medium web temperature and moisture content on the MD tensile strength and MD stretch at tensile failure. The medium moisture content is represented by the 50%, 70%, and 90% Relative Humidity levels used to condition the samples prior to tensile testing. The three relative humidity levels correspond to average moisture content levels of 7.0%, 9.6%, and 13.9%, respectively. The tensile test instrument was equipped with a heating device that allowed the test specimen to reach the desired test temperature in 1 second. The medium test specimens were encased in aluminum foil to prevent moisture loss in the specimen during heating and testing. This experiment was designed to simulate the MD tensile property changes that occur in the medium web due to the preheating and the steam preconditioning on the corrugator.

The data shown in ***Figure 5.2*** are the average effect for three different commercial mediums. The data demonstrate that the tensile strength of the medium decreases with increasing temperature and with increasing moisture content. The MD tensile failure stretch increases with increasing moisture content. The stretch increases with increasing temperature up to about 220 deg.F. and then decreases, (16). The author is not certain whether this is a real effect or an artifact of the experimental technique. It is possible that the samples lost moisture at the higher temperature levels and, therefore, had a reduced measured stretch.

The next several references address the issue of the effect of the single-facer process variables on the characteristics of the fluted medium.

Figure 5.3 shows the effect of corrugating roll pressure, medium web tension, corrugating roll temperature, and medium moisture content on the spring-back of the flutes. Spring-back is indicative of the ability of the paper to retain the molded flute shape. The tendency of a fluted paper to attempt to elongate (straighten out) is representative of stresses remaining in the paper. The experiment was conducted using a modified concora test instrument. A strain gage was used to measure the spring-back force of the fluted web as it was leaving the nip between the corrugating rolls. Commercial mediums were used for the experimental testing.

The data show that higher corrugating roll pressure, higher corrugating roll temperature, and higher medium web moisture content all produced a more permanently formed flute shape, as indicated by the lower measured spring-back force. Higher medium web tension increased the spring-back force. The data indicate an interactive effect between the corrugating roll pressure and the medium web tension, and between the corrugating roll temperature and the medium web moisture content. The spring-back was independent of the medium web tension at corrugating roll pressures above 13 kN/m. The medium web moisture variable had a greater magnitude effect on spring-back at higher corrugating roll temperatures, (81).

The data shown in ***Figure 5.4*** were also generated using a concora test instrument and handsheets made with corrugating medium pulp. In this experiment, the spring-back force of the fluted medium was quantified by measuring the final equilibrium length of the unsupported, fluted test strip. The data are expressed as the equilibrium length of the fluted strip as a percent of the original, unfluted test specimen length. A higher percent value indicates a greater spring-back tendency. The data show that both a higher corrugating roll temperature and a higher medium web moisture content reduced the spring-back, (95).

Figure 5.5 shows the effect of the medium web moisture content during fluting on the MD tensile strength of the fluted medium. The tensile strength of the fluted medium decreases as the moisture content of the medium web being fluted increases. This indicates that a higher medium web moisture content at the infeed side of the corrugating rolls makes the medium web more prone to MD tensile failure during fluting, (95).

Figure 5.6 shows the effect of the corrugating roll temperature on the concora strength of the fluted medium. The experimentation was done using a concora test instrument and handsheets made from corrugating medium pulp. The concora strength of the fluted medium increases with increasing corrugating roll temperature, (95).

Figure 5.7 is a multiple regression equation which correlates selected corrugating process variables to the flat crush strength of the fluted medium. Since the initial unfluted medium concora strength appears in the regression equation and is a constant for a given me-

FIGURE 5.2
Effect of Temperature and Humidity on Medium MD Tensile and Stretch

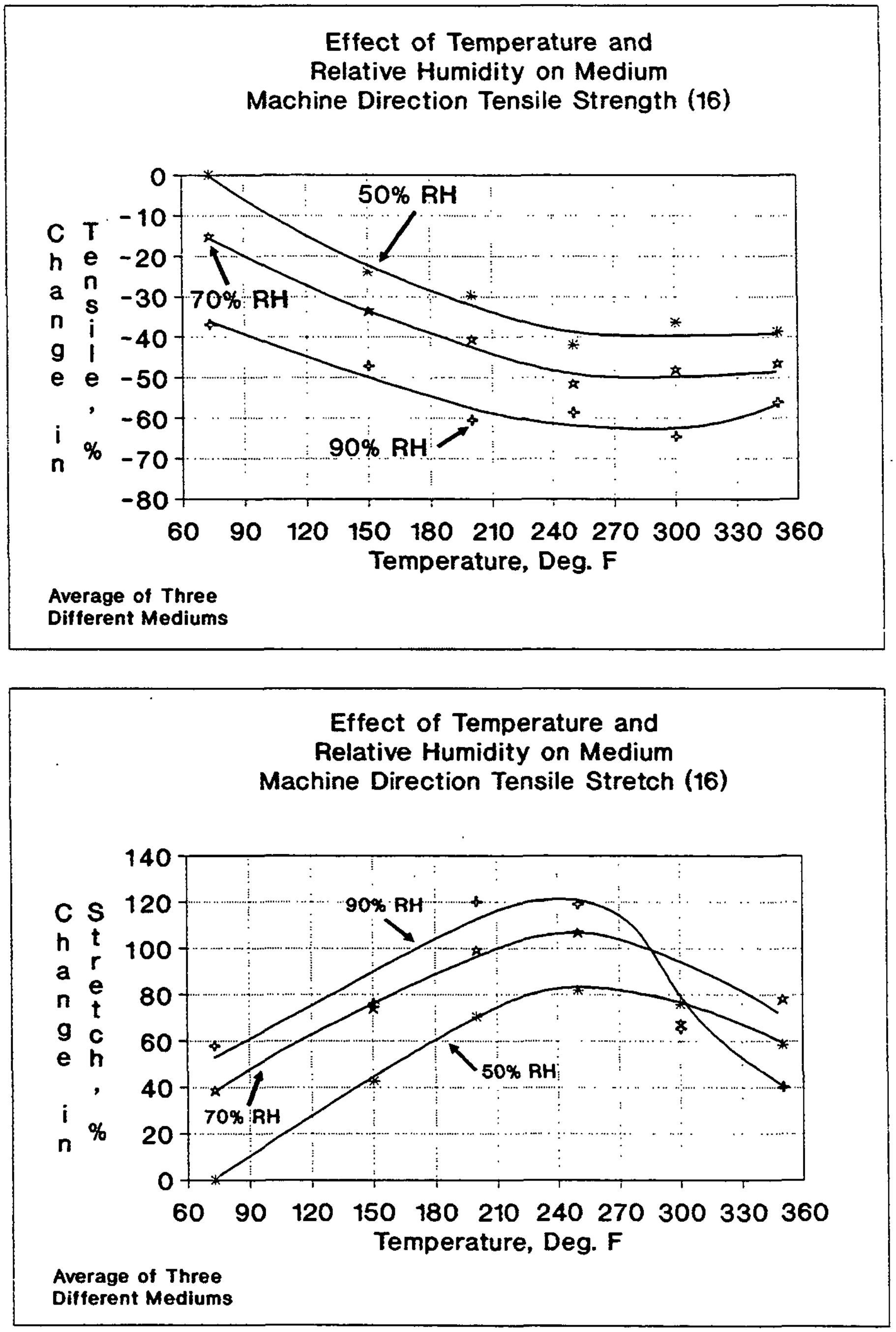


FIGURE 5.3
Effect of Corrugating Variables on Spring-back of Fluted Medium

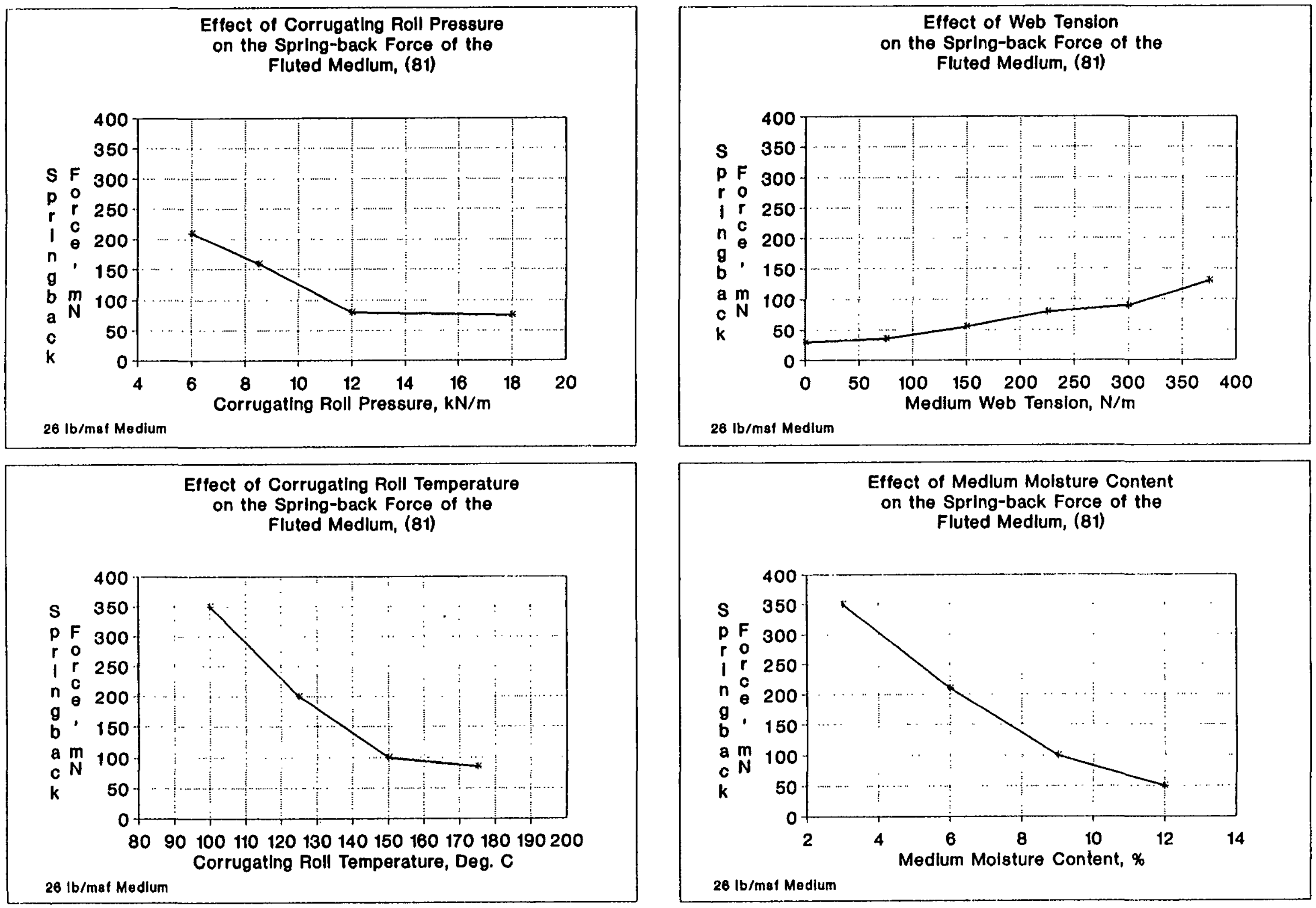
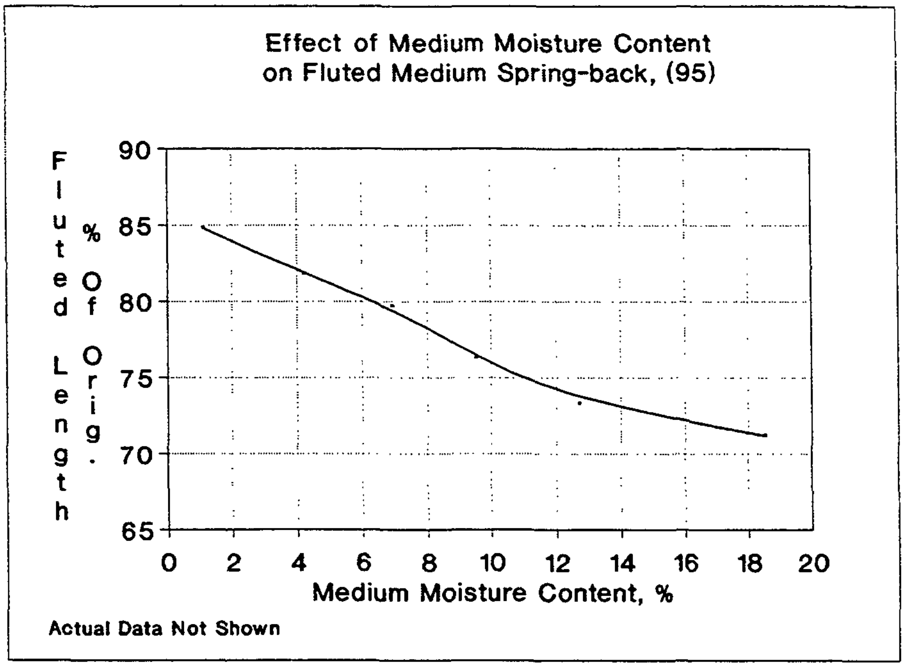


FIGURE 5.4
Effect of Corrugator Process Variables on Fluted Medium Springback



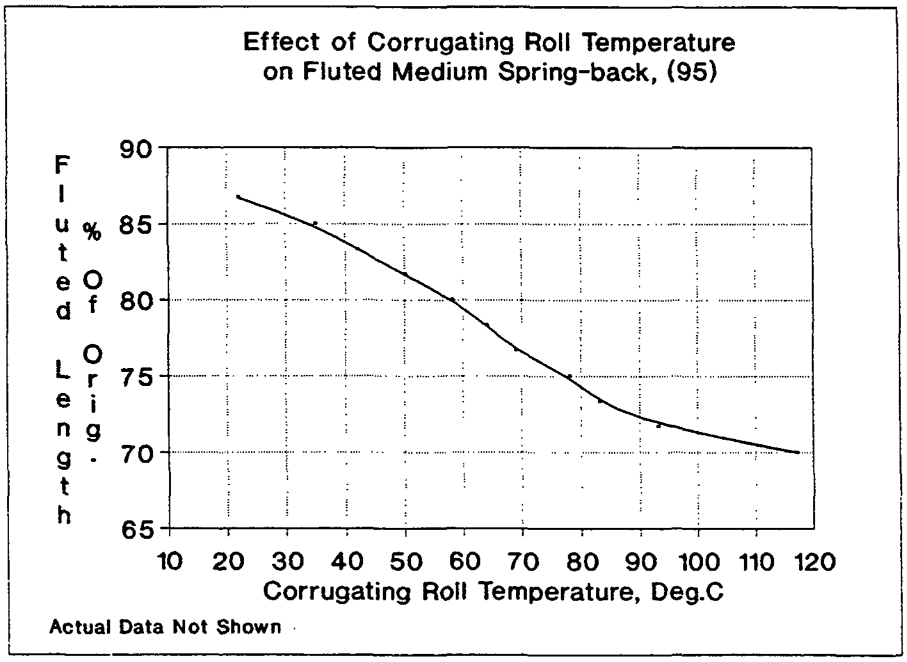


FIGURE 5.5

Effect of Medium Web Moisture Content on MD Tensile of Fluted Medium, (95)

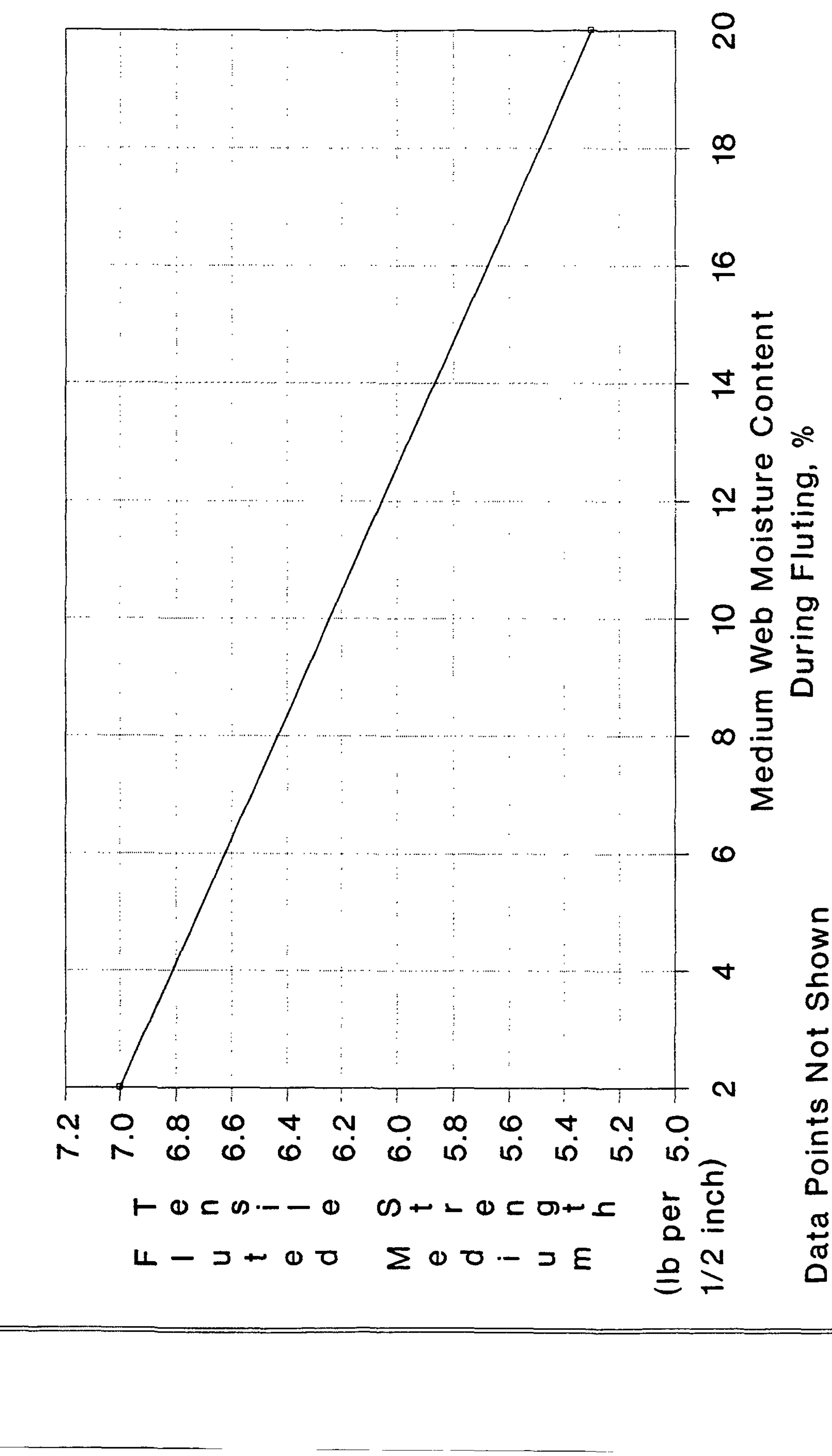


FIGURE 5.6
Effect of Corrugating Roll Temperature
on Medium Concora Strength, (95)

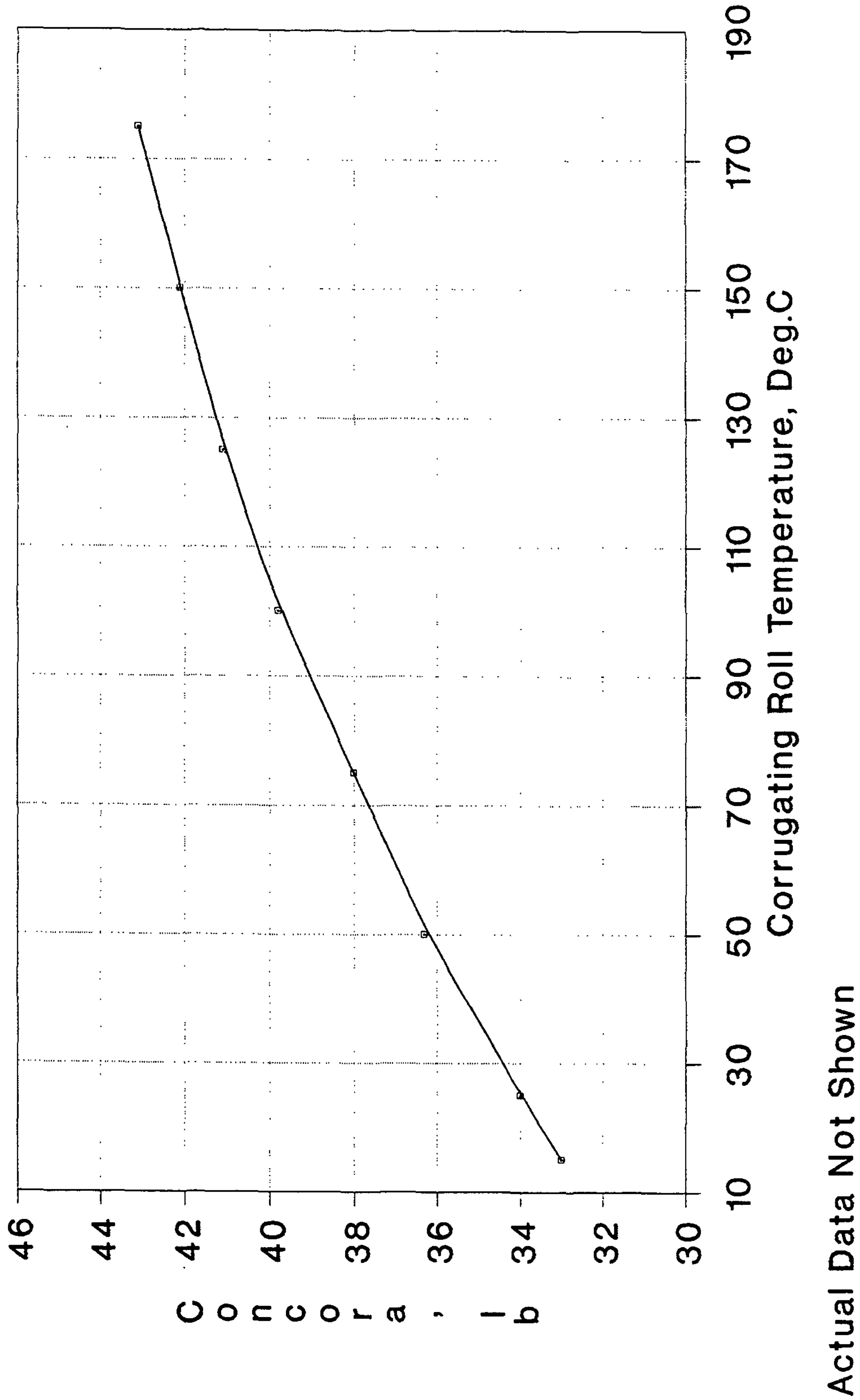


FIGURE 5.7
Effect of Corrugating Conditions and Medium Properties on Flat Crush, (16)

$$FC = a(A) + b(B) - c(C)^2 + d(D) + e(E)^2 + f(F) - g(G)^2 + h(H) - 37.5$$

$r^2 = 0.82$

a = 0.00168	A = Speed, fpm
b = 1.58	B = Nip Moisture Content, %
c = 0.0443	C = B
d = 0.292	D = Nip Temperature, Deg.F
e = 0.00088	E = D
f = 1.35	F = Roll Moisture Content, %
g = 0.0854	G = F
h = 0.555	H = Concora, lb

FC = Flat Crush, psi

dium material, a higher calculated flat crush strength for the fluted medium represents an improvement of the retention of this property after fluting. The data were generated on a pilot-size single-facer using commercial corrugating mediums. The regression equation indicates that a higher medium moisture content and a higher medium temperature at the point of fluting are beneficial for retaining flat crush strength, (16).

Figure 5.8 shows the relationship between the retention of crush strength after fluting and properties of the original medium. The crush retention is expressed as the ratio of the fluted to unfluted medium compressive strength. While the paper is not clear, it appears the crush strength referred to is the MD flat crush. The experimental data were generated using 26 lb/msf commercial corrugating mediums, and 26 and 40 lb/msf Formette handsheet mediums made from commercial medium furnishes. The corrugating was done on a pilot-size single-facer. A total of 19 different medium materials were tested. The results show that the compressive strength retention of the medium, after fluting, is correlated to the MD elastic modulus, the ZD elastic modulus, the basis weight, and the density of the unfluted corrugating medium. The crush strength retention is improved by a higher ZD modulus and density, and by a lower MD modulus, basis weight, and caliper, (29).

Figure 5.9 is an experimentally generated regression equation which correlates unfluted medium properties to the CD crush strength retention of the medium after fluting. The CD crush strength retention is expressed as the ratio of the medium fluted edge crush to the medium unfluted ring crush. A higher ratio is favorable. The equation is based on data generated by the corrugation of 26 lb/msf commercial mediums and formette handsheets, made from commercial medium furnish, on a pilot-size single-facer. The medium furnishes evaluated were NSSC, Green Liquor, Caustic Carbonate, and Recycled. The regression equation indicates that the CD medium crush retention is improved by a higher MD elastic modulus, a higher CD elastic modulus, a lower density, and a higher in-plane poisson ratio, (1).

The STFI short-span compression test instrument was used to measure the change in the compressive strength of the medium resulting from the fluting operation. The STFI test uses a specimen test span of 0.7 mm. This small span allowed compression tests to be measured on the sidewall areas of the flutes. The compression values for the fluted material were compared to those for the same corrugating medium before fluting. The fluting was done on a pilot-size single-facer using four different 26 lb.msf commercial mediums, (30).

The test data show that the MD STFI compressive strength (Flat Crush Test related) is reduced by an average 42% (35% to 50% range) by fluting the medium. The CD STFI compressive strength (Edge Crush Test related) is reduced by an average 18% (15% to 20% range) by fluting the medium. The MD short-span tensile strength was reduced by an average of 29% due to the fluting process. This is considerably less of a strength loss than the 42% loss in MD short-span compressive strength. The thickness (caliper) direction tensile strength (ZDT) also shows a reduction in strength due to the fluting process, (30). These two observations indicate that the loss in medium strength due to fluting is due mainly to the breakage of the fiber-to-fiber bonds. This debonding is apparently not fully recovered by the transverse compression of the medium at the tangential contact point between the two corrugating rolls, (see ***Figure 5.1***).

Figure 5.10 is a plot of the MD STFI compressive strength of the fluted medium against the measured flat crush of the same fluted medium. The good correlation between the two properties shows that the change in the short-span STFI compression test values between the unfluted and fluted medium is a good predictor of flat crush strength change expected due to fluting, (30).

Figure 5.11 shows that the medium spring-back measurement is a good predictor of the fluted medium concora strength. This indicates that the effects of the corrugating process variables on fluted medium spring-back shown in ***Figure 5.3*** and ***Figure 5.4*** should directly translate into fluted concora strength effects, (95).

Figure 5.12 shows the effect of the paper mill process variables of pulp refining and paper machine wet pressing on the retention of MD flat crush strength after fluting on the corrugator. ***Figure 5.13*** is a similar plot for the retention of CD edge crush strength.

The data show that increased refining improved the retention of the MD flat crush potential of the original medium by 3 percentage points, and increased the retention of the CD edge crush potential of the original medium by 24 percentage points. Similarly, the data show that increased wet pressing decreased the retention of the MD flat crush potential of the medium by 6 percentage points, and increased the retention of the CD edge crush potential of the medium by 5 percentage points. The data show that the combined densification of the medium by refining and wet pressing improves CD strength retention after fluting by 29 percentage points, and decreases the MD strength retention by 3 percentage points, (15).

The author is tempted to speculate on the implications of these results with respect to the relative importance of fiber-to-fiber bonding versus fiber strength, but

FIGURE 5.8
Effect of Medium Properties on Medium Crush Strength Retention, (29)

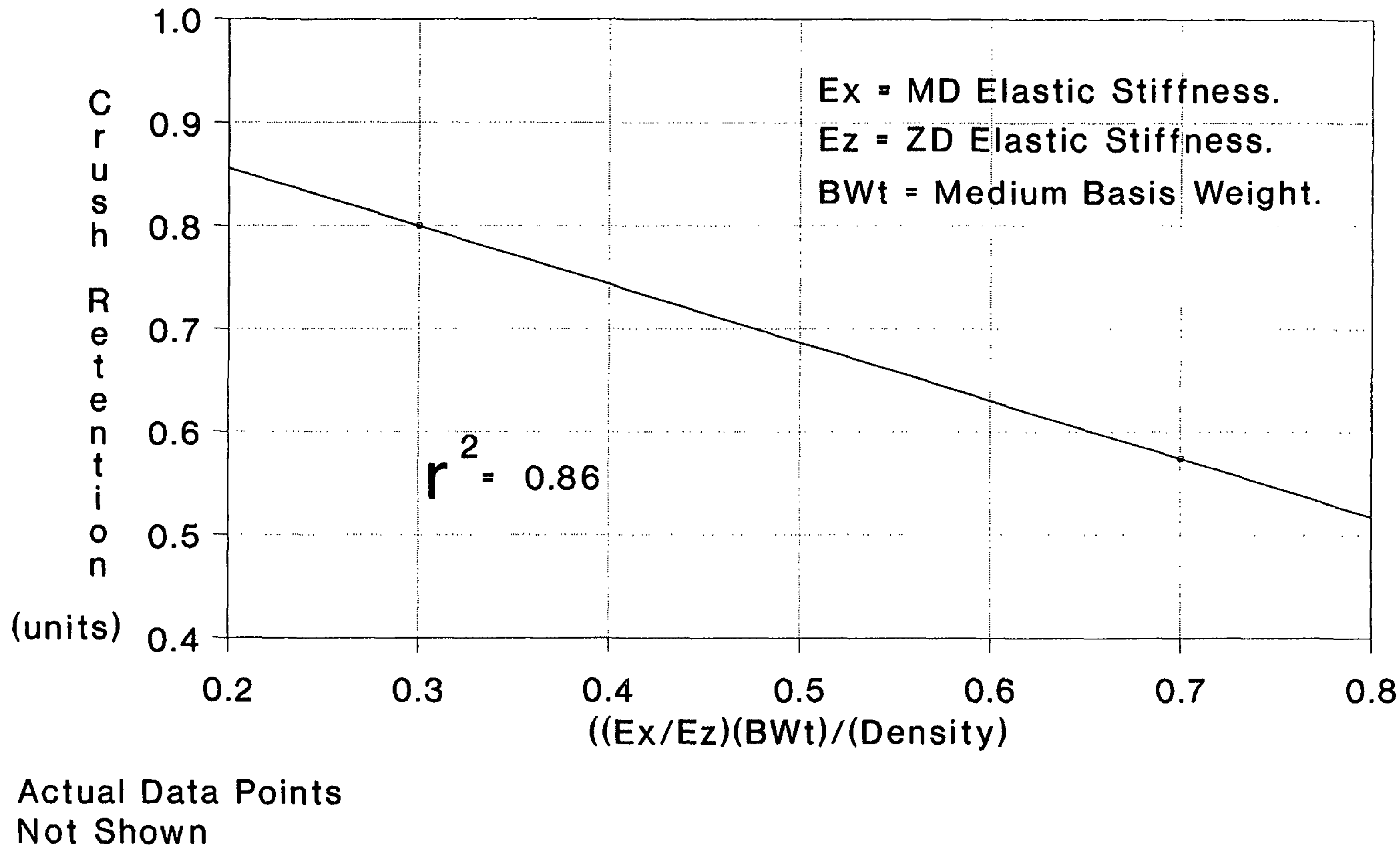


FIGURE 5.9

Effect of Medium Elastic Properties on Retention of CD Crush Strength After Fluting, (1)

$$CR = 1.35 - a(1/A) - (b + c(C))(1/D) - e(1/E) + f(F)(G)$$

$$r^2 = 0.636$$

CR = (Fluted Edge Crush)/(CD Ring Crush), Both In lb/6 inch

a = 0.385
b = 0.326
c = 0.365
e = 0.0060
f = 0.00037

A = MD Modulus, GPa
C = Density, g/cubic cm
D = CD Modulus, GPa
E = ZD Modulus, GPa
F = XY Poisson Ratio
G = Corrugating Speed, fpm

FIGURE 5.10
Relationship of MD STFI Compression of Fluted Medium to Flat Crush, (30)

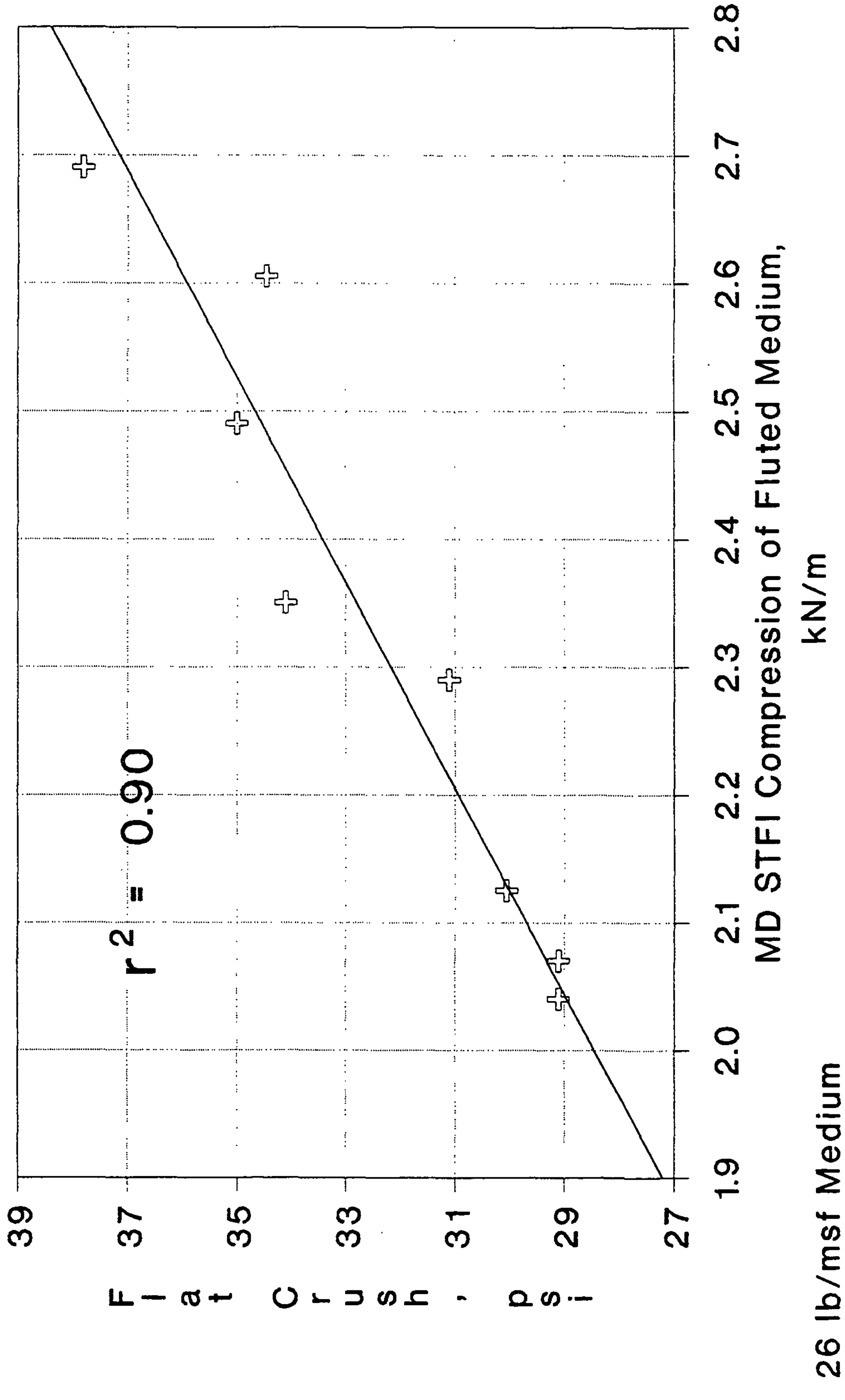
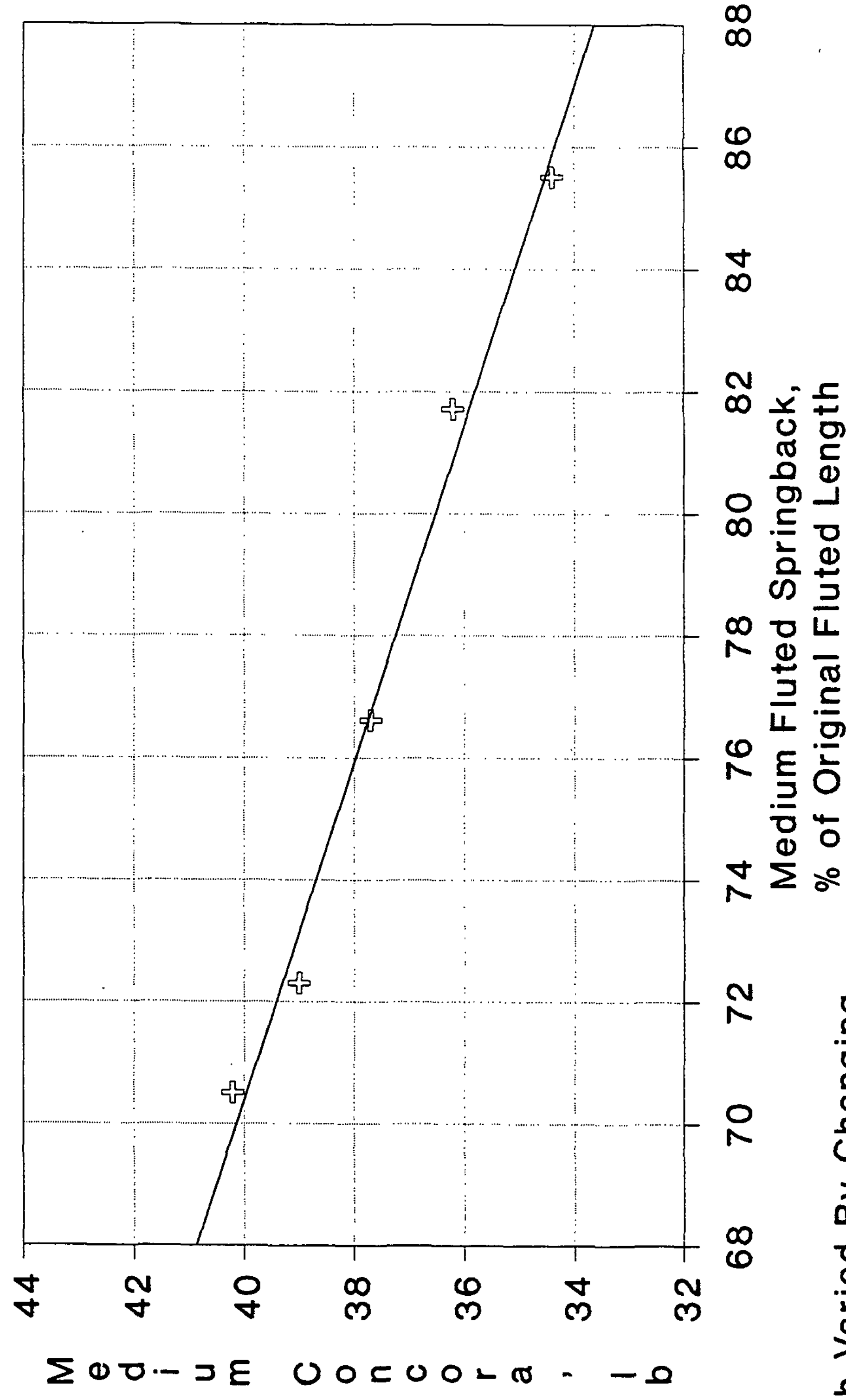


FIGURE 5.11

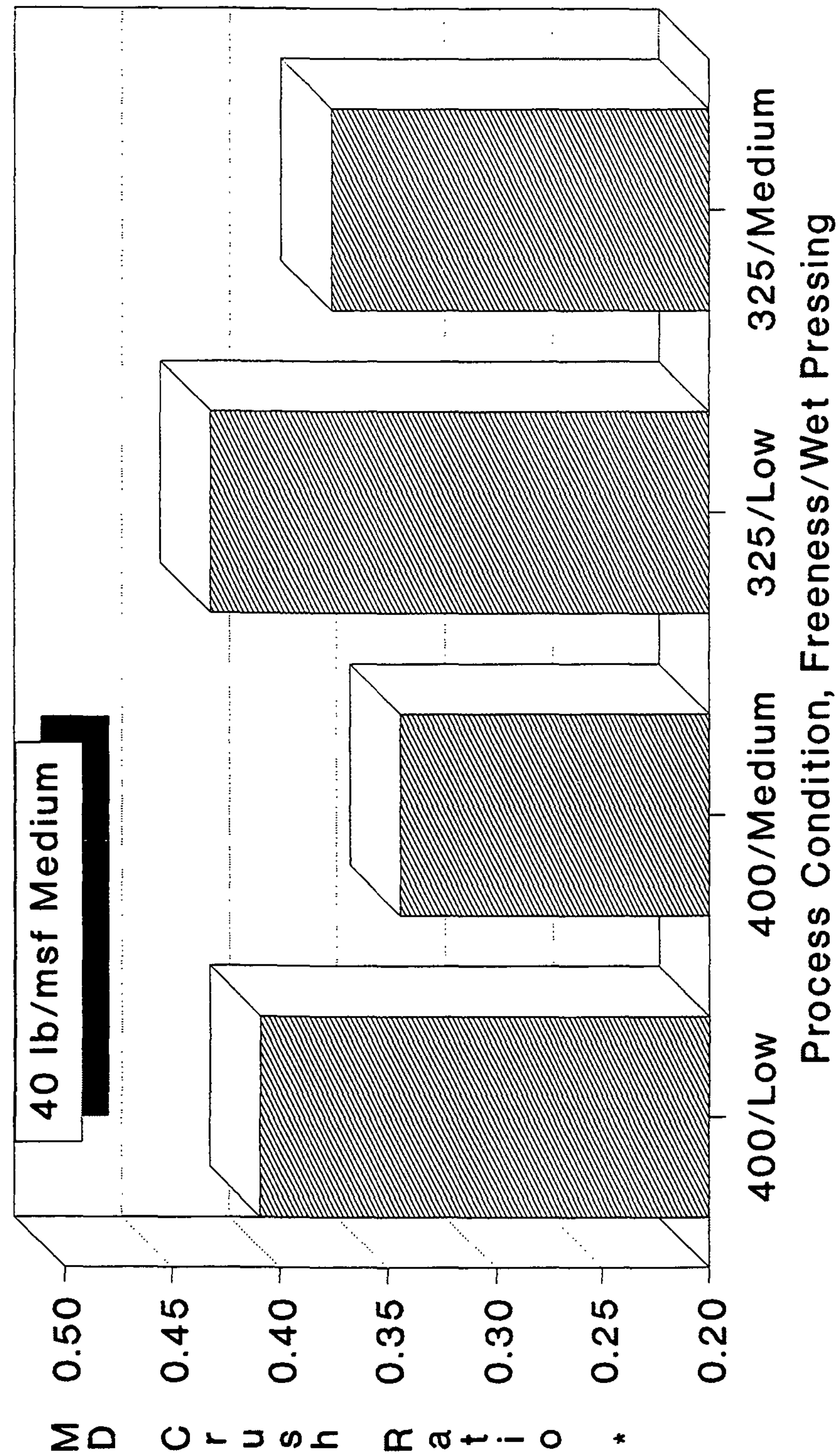
Relationship Between Medium Spring-back and Medium Concora Strength. (95)



Both Varied By Changing
Corrugating Roll Temperature.

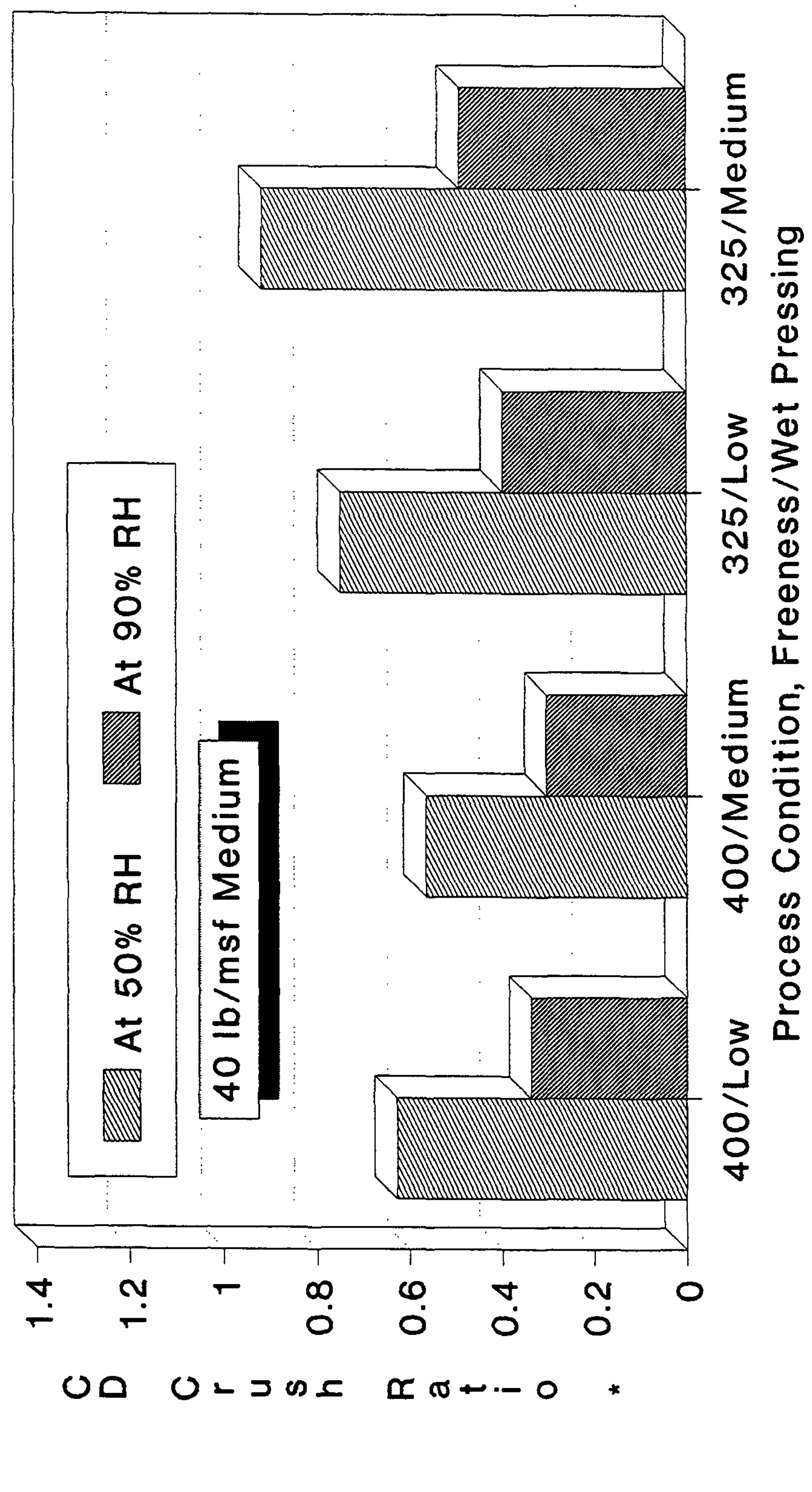
FIGURE 5.12

Effect of Refining and Wet Pressing on Flat Crush Retention After Fluting. (15)



* Flat Crush (psi) Divided By Concora Crush (lb)

FIGURE 5.13
Effect of Refining and Wet Pressing on
Edge Crush Retention After Fluting



* ECT (lb/inch) Divided By
CD Ring Crush (lb/6 inch)

he will leave this analysis to the reader. It has been suggested that the medium needs to have adequate interfiber bonding and fiber flexibility, good plasticity with heat and moisture, and good formation, (95).

The paper mills have been moving in the direction of increased wet pressing to improve the medium CD and MD crush strength and to improve the paper machine productivity. Wet pressing improves both MD and CD average crush strength of the medium rollstock. The data shown in ***Figure 5.12*** and ***Figure 5.13*** suggest, however, that the relative strength improvement actually achieved in the corrugated board, due to wet pressing effects, will be less than supposed for flat crush and greater than supposed for CD edge crush. This may explain some of the anecdotal experiences heard from the box plant personnel about some of the new "high crush" medium grades that are being offered. Some statements have been offered that the ECT is fine but that the Flat Crush is low.

The major corrugating process and corrugating medium properties affecting the strength retention in the corrugating medium after fluting are summarized in ***Table 5.2.***

The summary of the data discussed in this chapter indicates that more of the inherent strength of the corrugating medium will be retained in the corrugated board by employing the proper control of selected single-facer process conditions. These are the major process factors which enhance the flute molding characteristics of the corrugating medium. The information in the literature identifies these major process factors as heat, moisture, forming pressure and web tension. Improvement in strength retention after fluting can also be affected by those medium properties which minimize the flute forming stresses. The information in the literature identifies these major material properties as reduced caliper and increased stretch at tensile failure.

There was significant debate in the industry, during the consideration of Alternate Item 222/Rule 41, concerning the "correct" quantitative relationship between the linerboard and medium component CD crush-strength and the combined board Edge Crush Test. It seemed that each person had his/her own equation. It is interesting to speculate on how much of the disagreement can be attributed to the effect of the fluting process variables discussed in this chapter. The same type of conjecture can be made as to disagreement over predicting the flat crush strength of combined board from the medium concora strength.

Table 5.2. Major Corrugating Process Variables and Medium Properties Affecting Medium Strength Retention After Fluting

Variable	Direction of Change in Variable to Improve the Strength Retention	References
Corrugating Roll Pressure	Increase	68, 81
Medium Web Temperature	Increase	16, 38, 68, 81, 95
Medium Web Moisture Content	Increase	16, 81, 95
Medium Web Tension	Decrease	68, 81
Medium Tensile Strength	Increase	16, 29, 31
MD Tensile Stretch at Failure	Increase	16
Medium Density	Increase	29, 38
Medium Caliper	Decrease	15, 29, 38

Chapter 6

Bonding Theory

Bonding or adhesion is simply the process of having one material stick to another material, (119). For the corrugator bond, this involves having the tips of the fluted medium stick to the linerboard facings at two locations, the single-facer and the double-backer. These bonds make the combined material a corrugated structure and the package a corrugated box. Without the bonds, the package would be a three-ply multiwall bag. The objective of the corrugator bonding process is to obtain a consistent, strong, tough (not brittle) bond that will lower waste costs, increase corrugator productivity, and provide a more consistent performance package product, (12, 14, 47, 71, 79, 83). The corrugator productivity is affected by the bonding process since the corrugator speed is generally governed by the rate of adhesive tack development and the rate of bond strength development, (12, 67, 76).

Some people have suggested a fourth objective, specifically, to minimize starch consumption and cost. They point out that the application of too much adhesive can cause poor print quality if the combined board exhibits washboarding, and can promote excessive crushing if the medium is still damp during slotting and scoring, (14, 71, 79, 83). A thicker adhesive application also increases the bond setting time, (148). The author agrees that an application of an overabundance of adhesive should be avoided for the reasons stated above and also because of the adverse effect on warp. However, the starch adhesive is one of the least expensive materials used in a box plant. The author believes that attempts to absolutely minimize the adhesive application and thereby save pennies will produce dollars of added cost due to excessive box plant waste and poor package performance

Studies have shown that the formation of the corrugator bond is a complex process that is affected by the properties of the paper and adhesive, and by the corrugator process variables of heat, moisture, pressure, and speed (time), (20, 21, 22, 47). The corrugator bonding process can be described by seven major steps, as shown in ***Table 6.1***, (21, 24, 35, 47, 67, 119, 148).

The bonding theory that will be discussed applies equally to both the single-face bond and to the double-face bond. The one exception is the type and duration of the pressure applied to the bonded area as the bond sets. The single-face bond is under pressure only at the nip between the lower corrugating roll and the pressure roll in the single-facer for a fraction of a millisecond. The double-face bond is under lower pressure for a minimum of 6 seconds as the board passes through the hot plate and cooling sections of the double-backer.

Table 6.1. Seven Major Steps in the Corrugator Bonding Process

1. Select Adhesive.
2. Select and Treat Substrate (Heat, Moisture).
3. Apply Adhesive to Substrate.
4. Adhesive "Wets" the Substrate.
5. Adhesive Penetrates the Substrate.
6. Adhesive Starts to Set (Green-Bond).
7. Cured Bond Forms.

A silicate adhesive was used for bonding on the corrugator from 1879 until the mid-1940s, at which time a starch-based adhesive replaced the silicate adhesive. The starch-based adhesive is still in use today. On average, the starch adhesive slurry contains 78% water, 21% starch, 0.5% borax, and 0.5% caustic. The starch portion consists of 3 percentage points of cooked, pregelled carrier starch and 18 percentage points of uncooked, raw pearl starch. One function of the carrier starch is to hold the pearl starch granules in suspension, (45, 67, 76). The quality of the adhesive slurry is generally controlled by measuring its solids content, its Stein-Hall cup viscosity, and its gel point. It is interesting to note that an adhesive application rate of 2.2 lb/msf starch solids on a 42-26-42 lb/msf C-flute construction adds 6.7% water to the combined board.

The substrates consist of the single-face linerboard, the fluted corrugating medium web, and the double-face linerboard. The temperature of the three webs is controlled by the use of linerboard, medium and single-faced web preheaters, by the heated corrugating rolls and pressure roll, and by the hot plates of the double-backer. The moisture is affected by the various heating sections previously mentioned and by the steam showers and the water associated with the adhesive slurry.

In general, the adhesive slurry is applied to the tips of the fluted medium by an applicator roll. The film thickness on the applicator roll is controlled by the use of a metering roll. The adhesive film thickness on the applicator roll is affected by gap setting between the two rolls, by the ratio of the surface speeds of the metering roll to applicator roll, by the corrugator speed, and by the interaction of the ratio and the corrugator speed, (47, 57, 60, 61, 71, 79, 83). There is a critical roll speed ratio at which the adhesive film thickness is independent of the corrugator speed. This critical speed ratio is related to the high shear viscosity of the adhesive. The Stein-Hall cup viscosity, commonly used in box plants for adhesive quality control purposes, does not measure the high shear viscosity of the adhesive, (47, 60, 61). An instrument is available to measure the high shear viscosity of the starch adhesive slurry in the box plant environment, (61).

Adhesive film instability patterns can also occur on the applicator roll surface. The two most common types are "ringing," which consists of bands of varying adhesive film thicknesses running around the circumference of the applicator roll and a "mottle" pattern, (70). Runout in the applicator roll or in the metering roll, due to defective bearings or bent shafts, will cause the adhesive film thickness to vary around the circumference of the applicator roll. This defect is often visible as a repetitive "strobe-like" barring on the surface of the turning applicator roll. The ringing and mottle defects also are generally visible on the turning applicator roll.

Adhesive consumption determinations are made in the box plant by measuring the volume of adhesive slurry consumed for a known area of several thousand square feet of corrugated board. This method yields an average application rate but does not provide information on application variability due to the instability patterns described above. Two laboratory starch adhesive measurement techniques are available for quantifying the smaller pattern variability in adhesive application. An iodide/iodine method is described in ASTM D-591 and TAPPI T-419. The other method utilizes a cobalt tracer in the adhesive, (71, 79, 83).

A liquid adhesive needs to wet the surface of the substrate materials and to increase the area of contact by spreading over the surface and flowing into the substrate pores in order to form a strong bond. (18, 24, 119, 148). The relative ability of a liquid to wet the substrate is determined by measuring the contact angle of a bead of the liquid against the substrate when contact is first made. The contact angle is the angle between the flat substrate and the bottom of the adhesive bead surface touching the substrate. A contact angle of 0 deg. indicates a spontaneous wetting and spreading of the liquid over the substrate surface. A contact angle of 90 deg. or greater indicates that the liquid will not wet the substrate surface and, therefore, will not bond to the substrate. Contact angles less than 90 deg. indicate varying wetting potentials, (24). The contact angle is reduced by a lower viscosity and/or a lower internal free energy of the adhesive, (67, 76).

Figure 6.1 shows a stylized representation of the stages that a corrugator starch adhesive goes through from the time that it is applied to the flute tip until the time that the final cured adhesive is formed. The plot is shown in terms of the energy required per pound of adhesive slurry and the temperature of the adhesive. The first 60 BTU, or 8.3% of the total process energy is required to raise the adhesive temperature from ambient to the gel point. This energy is for an adhesive with a gel point of 159 deg.F. A lower gel point adhesive would require less energy input in this stage, and a higher gel point adhesive would require more energy input. The temperature then remains constant as the raw pearl starch granules in the adhesive slurry gel. The gelling requires 20 BTU or 2.8% of the total process energy. The temperature of the adhesive then increases to the 212 deg.F. vaporization temperature of water by absorbing 62 BTU, or 8.6% of the total process energy. The water then evaporates from the bond area until the final dry, cured bond forms. This evaporation requires 582 BTU, or 80.4% of the total process energy, (24).

This type of energy plot does not directly address the development of the actual strength of the bond. The bond strength development stages are shown in ***Figure 6.2***, where bonding time is plotted against the adhesive viscosity. The adhesive viscosity is indicative of the tackiness of the adhesive. A higher viscosity has more tack or stickiness. The representation is not shown to scale.

The adhesive viscosity actually decreases for a short period of time as the temperature of the slurry increases, (45). The viscosity of free water decreases with increasing temperature. Once the gel temperature has been reached, the uncooked raw starch granules begin to absorb water and gelatinize; the viscosity and

FIGURE 6.1

Bond Setting of Corrugator Starch Adhesive, (24)

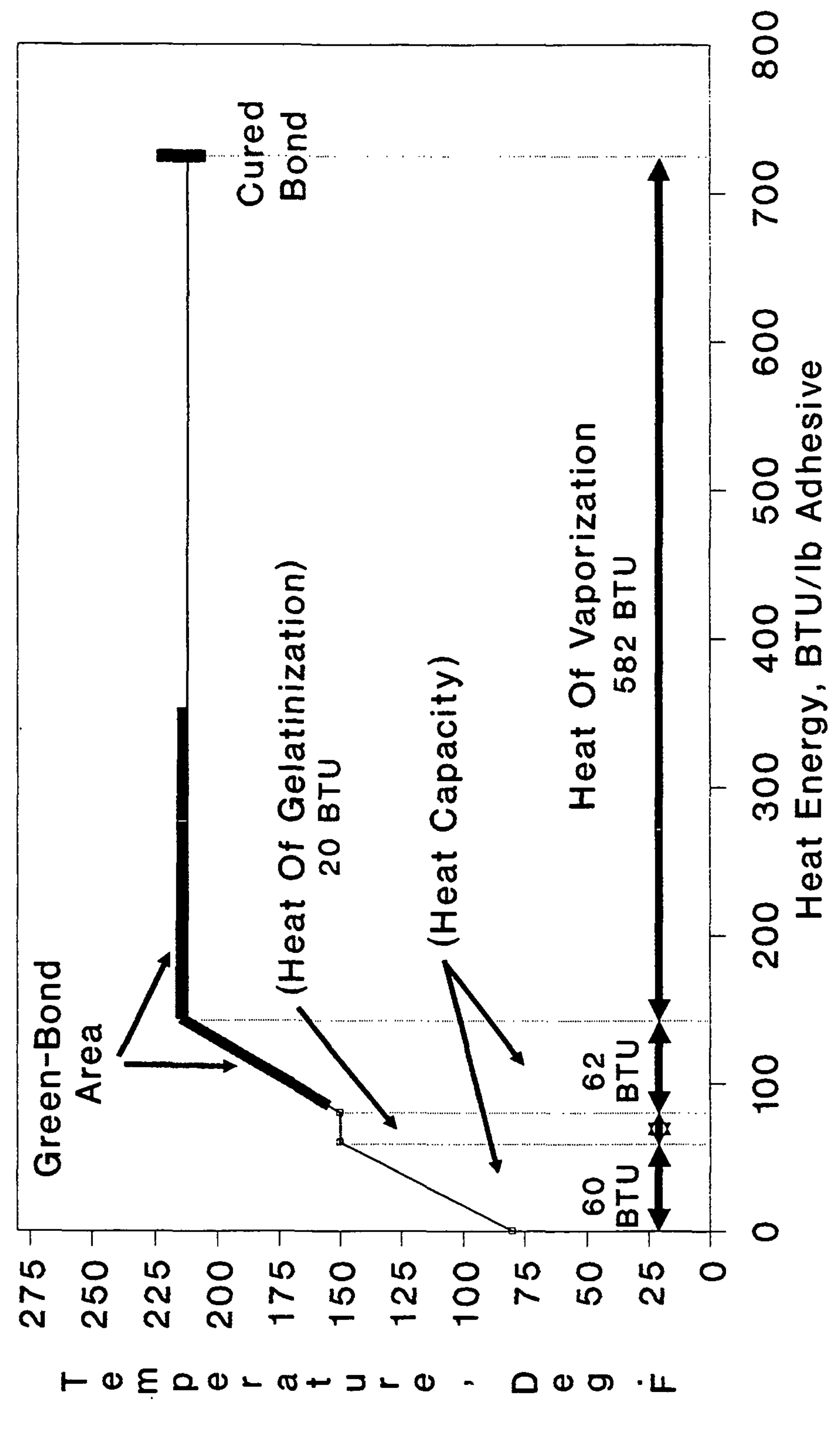
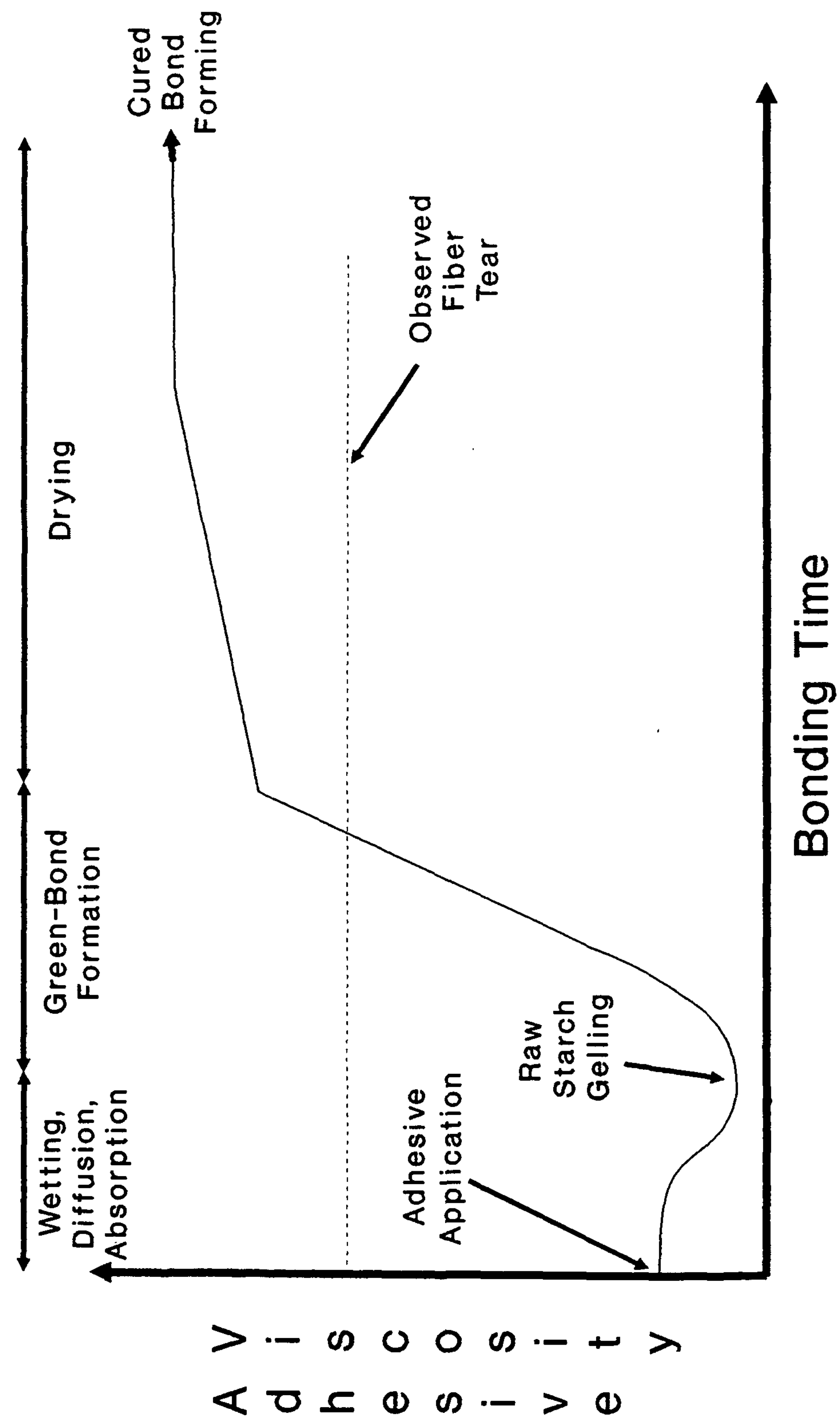


FIGURE 6.2
Green-Bond Development Theory, (45)



internal adhesion strength begins to increase rapidly; and the adhesive begins to become tacky. This is the bond formation stage commonly referred to as the "green-bond," (21, 24, 35, 45, 67, 76, 119, 148). The green-bond can be defined as the point where the "thermoplastic" adhesive film can withstand the shear and tensile forces due to the mechanical stresses induced by the corrugating equipment, (45). The start of the green-bond stage on one corrugator may or may not correspond to that of another corrugator, depending on their relative mechanical condition.

The viscosity increase that occurs at the gel point is associated with several different mechanisms. First, the conversion of the raw starch into cooked or gelatinized starch increases the viscosity of the total adhesive. Second, the cooked carrier portion of the original adhesive slurry can form a real adhesive film. Third, the raw starch acts as a "water sink" as it absorbs several times its weight in water as it swells. This reduces the free water content of the total adhesive and increases its total viscosity, (45, 67, 76). Fourth, when the raw starch absorbs water, the cooked carrier starch releases some of its originally bound water, due to equilibrium forces. The carrier starch concentration increases, and it releases film forming lower molecular weight starches to the free adhesive liquid. Fifth, the gelatinization of the raw pearl starch releases lower molecular weight starch molecules into solution. Under the correct heat and moisture conditions, these low molecular weight fractions can form an adhesive film, (67, 76). Microscopic examination of the cured glue lines has shown that various areas of the bond contain different proportions of gelled and ungelled starch granules, varying starch macromolecule structures, and differing starch molecular weight fractions, (21, 35, 48, 102, 117). Both the carrier and raw starch portions of the original starch adhesive slurry are important to the bond formation process, (67, 76).

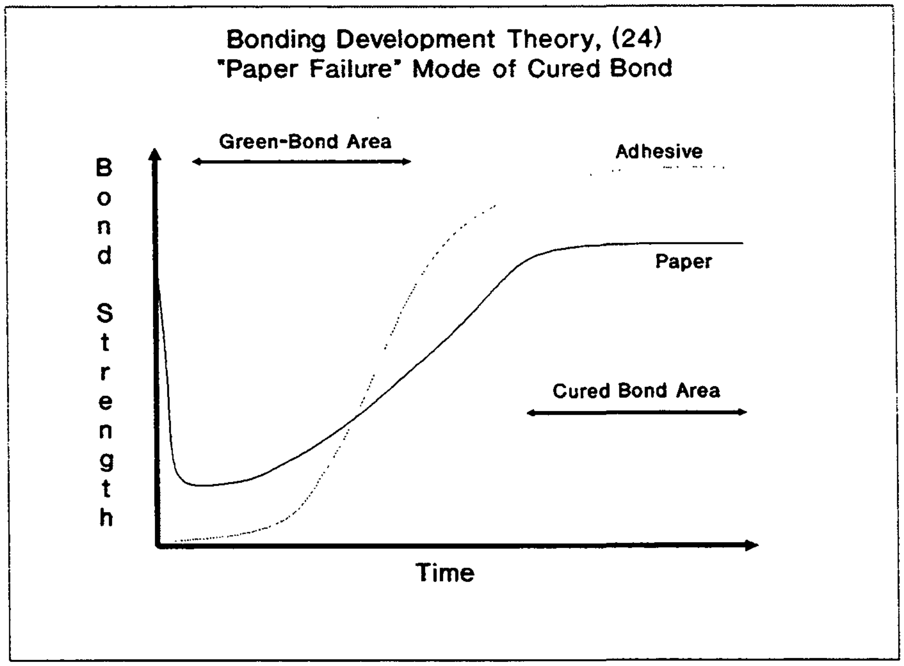
The final stage of bond development involves the removal of water from the bond site either by evaporation or by migration of the water into the paper, (21, 35, 67, 76, 119, 148). Once this has occurred, the final cured bond is formed and cannot get any stronger. Most people in the industry qualitatively judge the bond quality and potential strength by tearing apart a sample of combined board and looking for fiber tear. A deep linerboard fiber tear is considered especially desirable. Medium fiber tear or decapping of the flute tips is generally considered less desirable bond failure modes. It is felt that the bond can be no stronger than the ZD tensile strength of the linerboard. In fact, this may or may not be true depending on the moisture content of the sample at the time that the inspection is made.

The qualitative bond strength development curves in ***Figure 6.3*** show the internal adhesion strength of the two components, the paper and the adhesive, as a function of time. The internal self-bonding strength of the adhesive gradually increases with time as the adhesive passes through the five stages described above. The paper, on the other hand, loses some of its internal self-bonding strength as the water from the adhesive wets the paper and disrupts the fiber-to-fiber bonding. At some stage, the internal strength of the adhesive exceeds the strength of the paper and fiber tear occurs. The top graph in ***Figure 6.3*** represents a "good" bond situation. The adhesive strength remains above that of the paper in the cured bond stage of the process. The bottom graph depicts a "false good" bond situation. The adhesive strength exceeds the paper strength for some period in the green-bond region but does not exceed the paper strength in the cured bond region. The cured bond in this case would exhibit an adhesive bond failure mode or, as commonly stated in the industry a "brittle bond," (18, 24, 67, 76, 119). It has been suggested that this type of "false good" bond condition is increasing in the field with the advent of the highly densified, high crush strength paper grades and with the increased use of recycled fiber. It has been reported that the "brittle bond" is not seen in the sheets exiting the corrugator but appears after the sheets have remained in the stacks for a period of time and have dried out, (11).

Figure 6.4 shows the effect of paper moisture content on the bonding time required to achieve fiber tear. The data are based on a dextrin adhesive that sets solely through the loss of moisture from the adhesive. The data show that the time to observed fiber tear increases as the moisture content of the paper increases. This is caused by the reduction in the rate of moisture migration away from the glueline, (148). It is not uncommon for a corrugator crew to examine the double-back bond at the edges of the corrugator and to see separation of the bond in the adhesive. The adhesive tends to be thick and tacky, and the crew assumes that the bond will "setup" in the stacks. This assumption may or may not be correct. It may require considerable time before the true quality of the cured bond is known.

Figure 6.5 is a representation of the corrugator bond failure patterns observed in a large number of samples of commercial corrugated board. The nature of the failure modes are related to the measured pin adhesion strength of the cured bonds. Bond failure can occur in five different zones, within the glue film (brittle bond), at the glue/medium interface (little fiber pull), within the medium material (decapping), at the glue/linerboard interface (little fiber pull), and within the linerboard material (generally considered a good, "tough" bond). The data indicate that a minimum pin adhesion strength, using TAPPI sample conditioning and testing methods, of 6.5 psi is needed to generate linerboard fiber pull failure, (14).

FIGURE 6.3
Bond Development Theory
Failure Modes of Cured Bonds



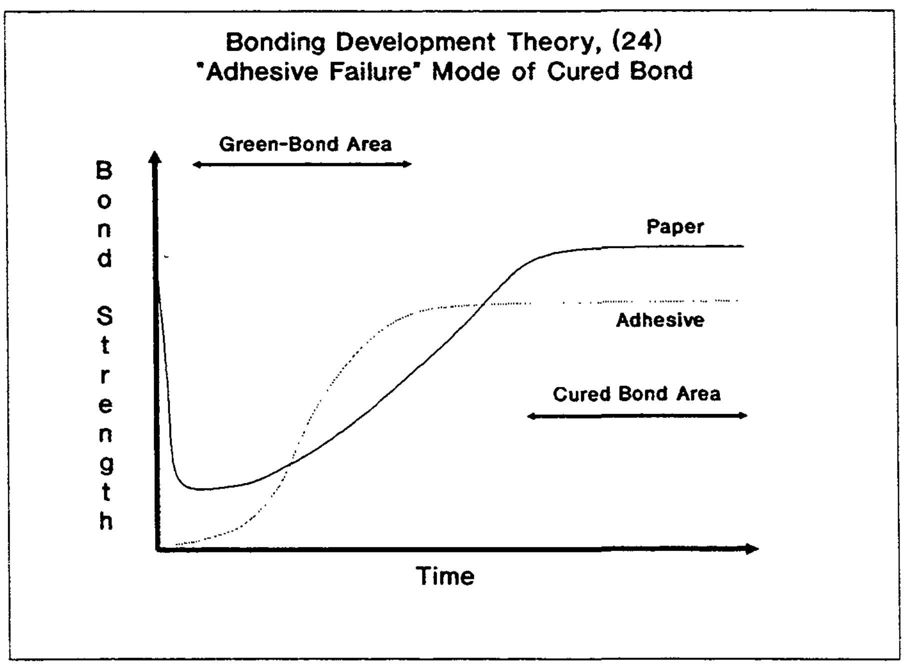


FIGURE 6.4

Effect of Paper Moisture Content on Time to Fiber Tear, (148)

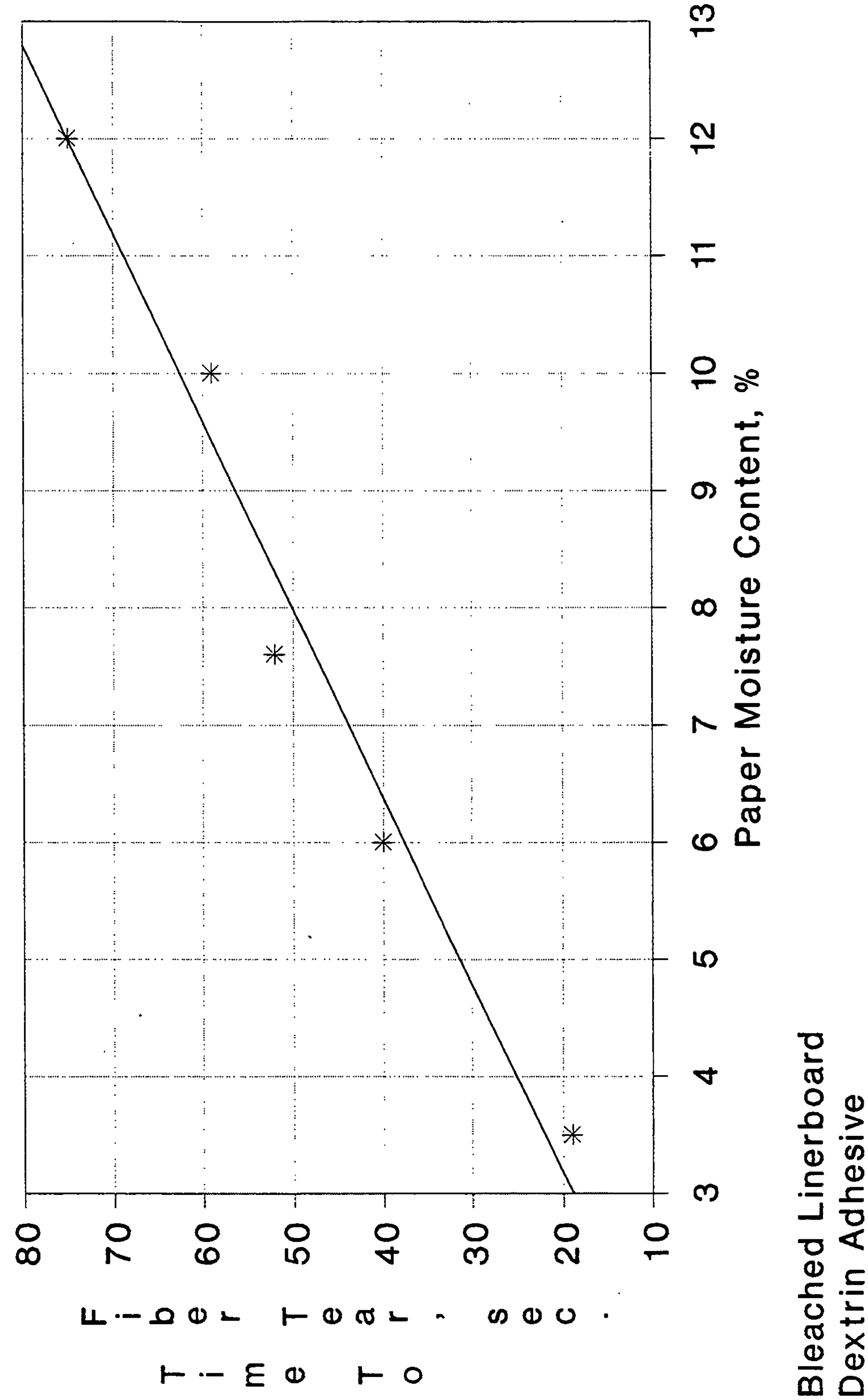
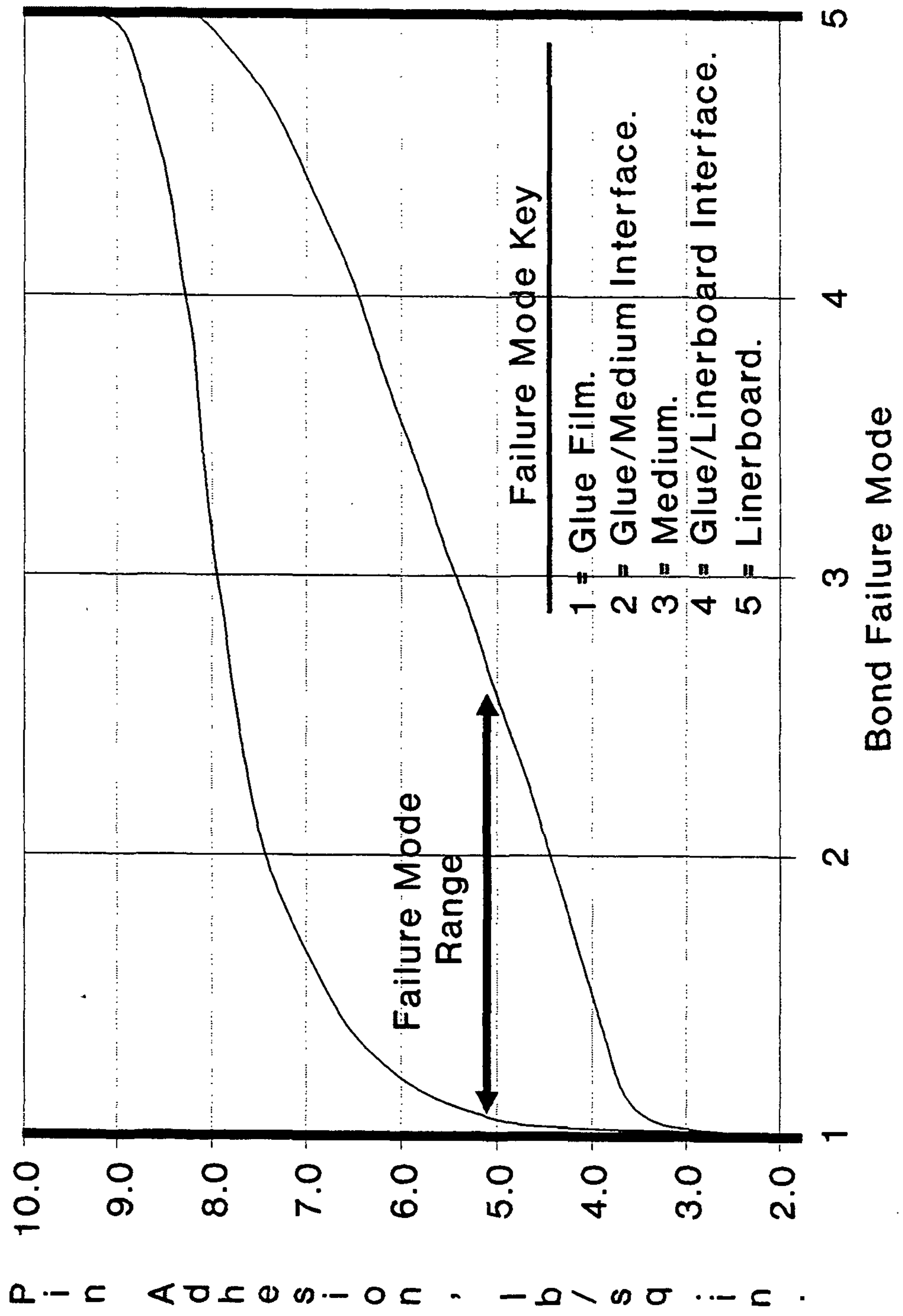


FIGURE 6.5

Single-Facer Bond Failure Modes, (14)



The effect of medium properties on the volume of adhesive transferred to the medium from the applicator roll is shown in ***Figure 6.6.*** The experiment was conducted using a bench top laboratory device. Three 26 lb/msf commercial corrugating mediums exhibiting different smoothness and liquid receptivity characteristics were selected for testing. The Roughness Index, Receptivity Index, and the Void Volume values for the three mediums are given in ***Figure 6.6.*** The Roughness Index varied by a ratio of 3:1; the Receptivity Index varied by a ratio of 12:1; and the Void Volume varied by 4.8%.

The data show that the adhesive volume transferred to the non-receptive medium did not increase with contact time after the first 1 second. This can be attributed to the lack of sufficient wetting of the medium surface by the adhesive. The two receptive mediums showed increases in adhesive transfer with increasing contact time, and the rate of increase was approximately equal for the two (equal correlation line slopes). The smoother sample, however, picked up 4.5 units less adhesive volume at all contact times, (104, 120). These results suggest that the adhesive application to a receptive medium, at constant glue station settings, will increase as the corrugator speed decreases (increased contact time with adhesive film on the glue roll). At constant corrugator conditions, a rougher surface medium will have more adhesive transferred to it from the glue roll than will a smoother surface medium, provided both are equal in receptivity, (18, 47, 119, 120).

The penetration of the adhesive into the medium is shown in ***Figure 6.7*** for the same experimental materials and conditions shown in ***Figure 6.6.*** The data shown are based on the average values for the combined 0.06 and 0.73 contact times. The bars represent the cumulative percent of total adhesive between the described depth into the medium and the application surface of the medium. The starch content data were generated by surface grinding of the medium samples and by the TAPPI T-419 starch analysis method. All three samples showed no starch presence beyond a depth of 6 mils. The only major difference in starch penetration between the different medium samples occurs at the 1.2 mils depth. The smoother surface sample had more surface starch, (120). It must be kept in mind that a deeper penetration of starch does not necessarily mean an improved bond strength. The starch deeper inside the medium may be low molecular weight components which do not contribute to bonding.

The data shown in ***Figures 6.6 and 6.7*** are based on the medium material before it has gone through the fluting process. As was discussed in <u>Chapter 2</u>, the medium at the flute tip, where the adhesive is eventually applied, is permanently compressed by the action of the corrugating rolls. The caliper of the medium in the flute tip area is reduced, on average, by 35%, as is shown in ***Figure 6.8.*** This compression may affect the receptivity of the medium to the adhesive and the penetration of the adhesive into the medium.

The same three medium materials that were used to generate the data shown in ***Figures 6.6 and 6.7*** were calendered using heated steel rolls. A caliper reduction of 32% was achieved. This calendering did not appreciably change the Receptivity Index of the three materials, but it did increase the smoothness. After calendering, all three materials had approximately the same smoothness. The effect of the calendering on the adhesive transfer to the medium and on the penetration of the starch into the medium is shown in ***Figure 6.9.*** The nonreceptive medium still picked up less adhesive than the receptive mediums. The percentage difference was the same as was observed for the uncalendered medium samples.

All three calendered mediums showed much higher percentages of the starch located closer to the surface of the medium than was observed for the respective uncalendered samples, (117). The results indicate that the caliper reduction which occurs at the flute tips does not affect the volume of adhesive transferred from the glue roll to the flute tip. Receptivity tests on various medium rollstock materials will be indicative of the relative performance, with respect to adhesive application, that is expected for the materials in the actual corrugating process. The compaction at the flute tip during fluting does reduce the adhesive penetration into the medium and negates the effect any surface smoothness differences measured for different uncorrugated medium materials.

Other researchers have investigated the starch penetration into the medium component of commercially produced corrugated board. The results of these studies indicate that most of the starch remains near the surface. Only the cooked starch components penetrate the medium to any great extent, (11, 14, 117). The results of starch penetration analysis on commercial corrugated board are summarized in ***Table 6.2***, (14). These studies confirm the laboratory results discussed above, (117, 120).

These experimental results serve to support the prior conclusion that the depth of starch penetration into the corrugating medium at the bond site is <u>not</u> a strong indicator of a good, strong, tough bond. Microscopic examination of the single-facer bond in commercially produced corrugated board shows three zones containing adhesive. The first zone is at the flute tip; the second zone is on the exterior of the flute sidewall; and the third zone is in the fillet region between the medium flute and the linerboard facing. The adhesive at the flute tip contains both cooked and uncooked starch. The uncooked starch is present because of the lack of

FIGURE 6.6
Effect of Medium Properties on
Adhesive Transfer to Medium. (120)

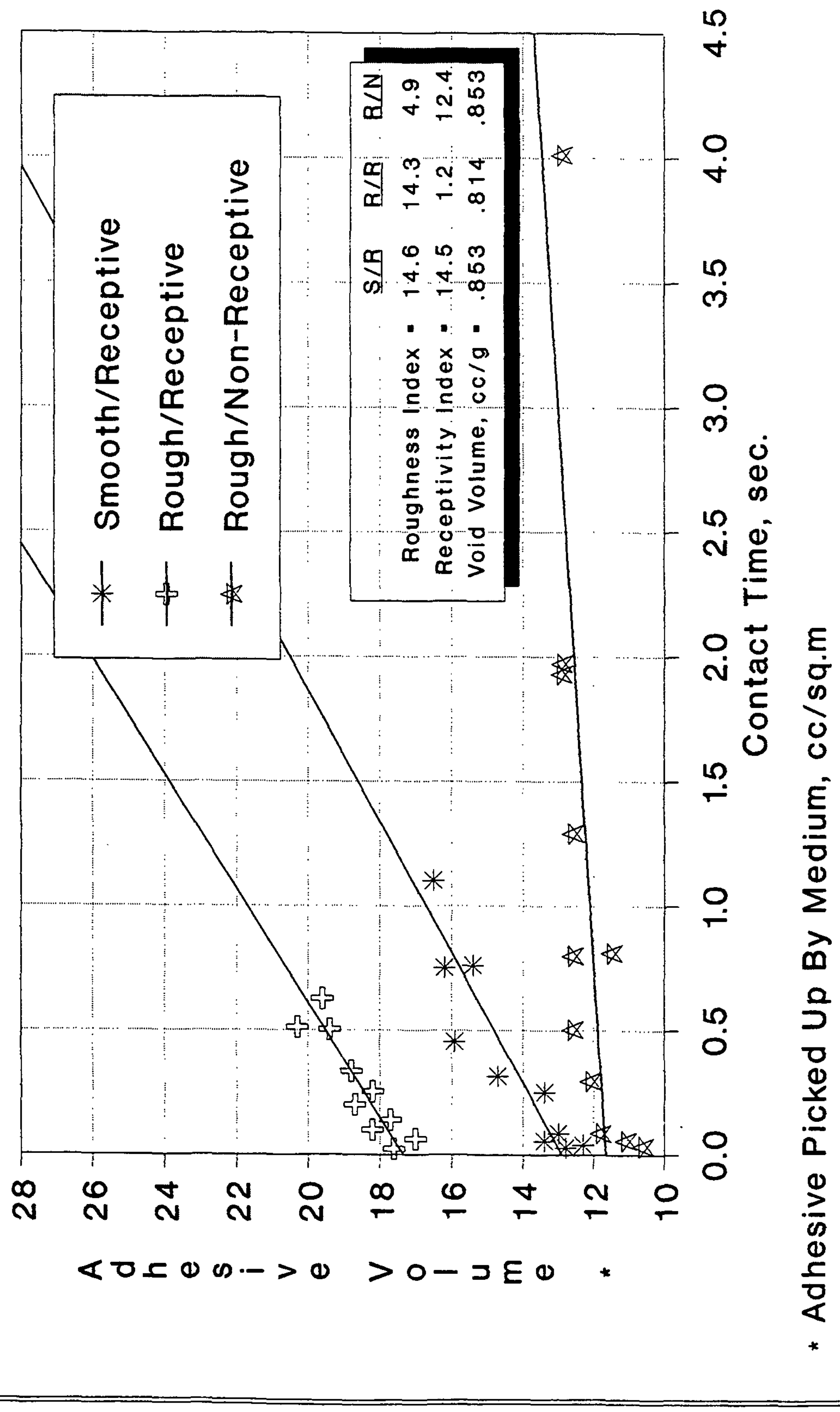


FIGURE 6.7

Effect of Medium Properties on Adhesive Penetration Into Medium, (120)

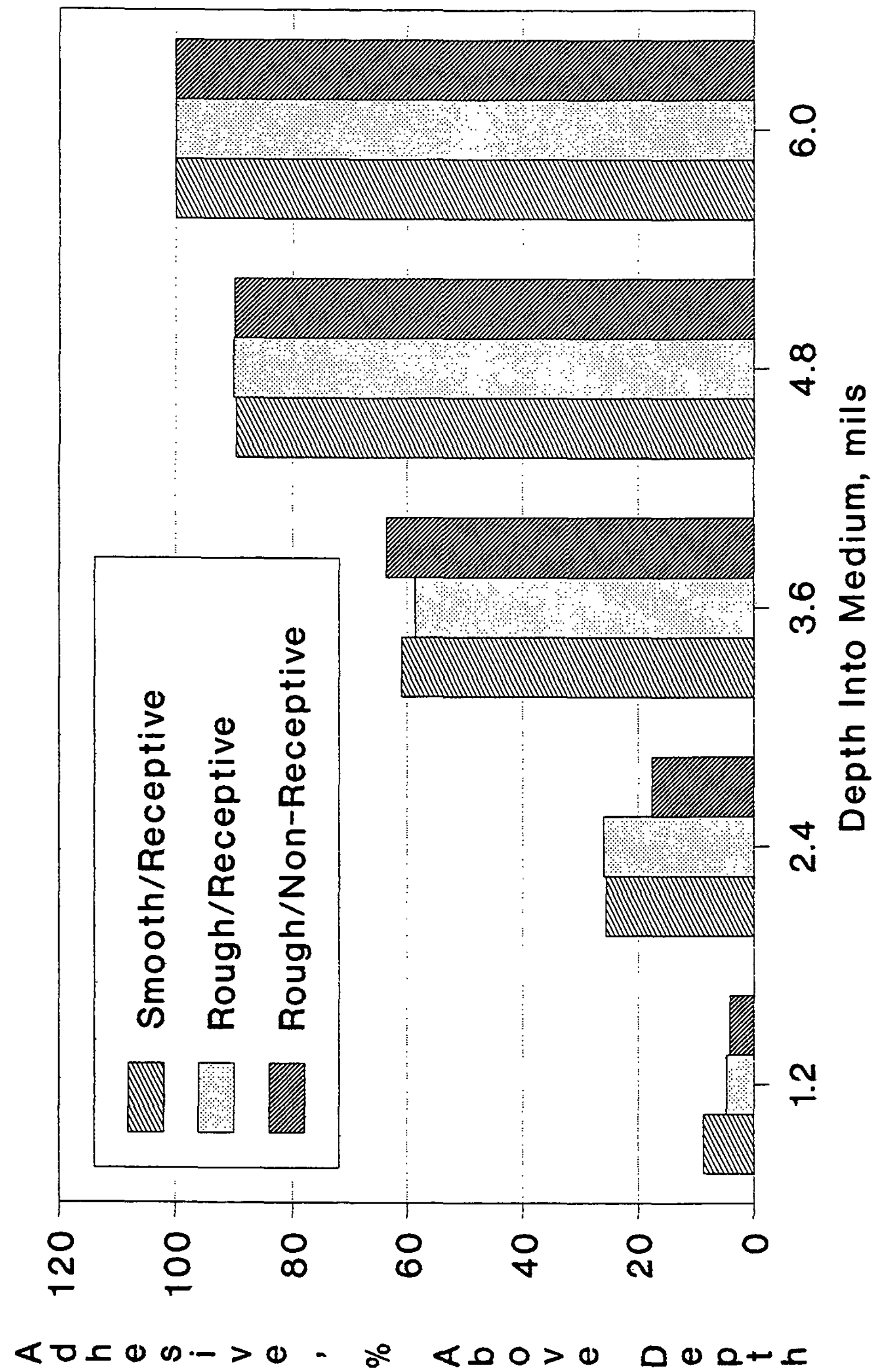


FIGURE 6.8
Permanent Transverse (ZD) Compression of Medium During Fluting. (145)

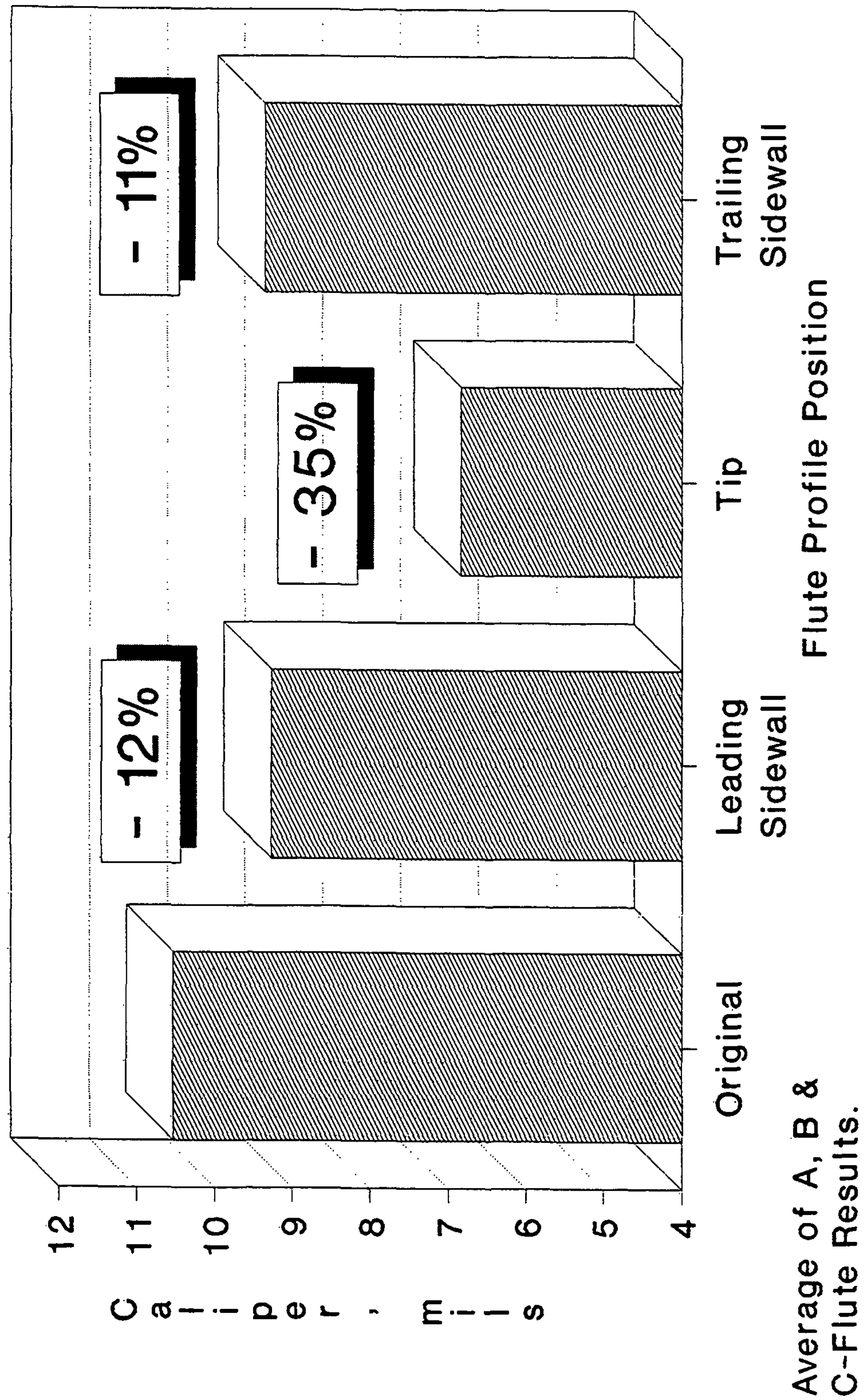
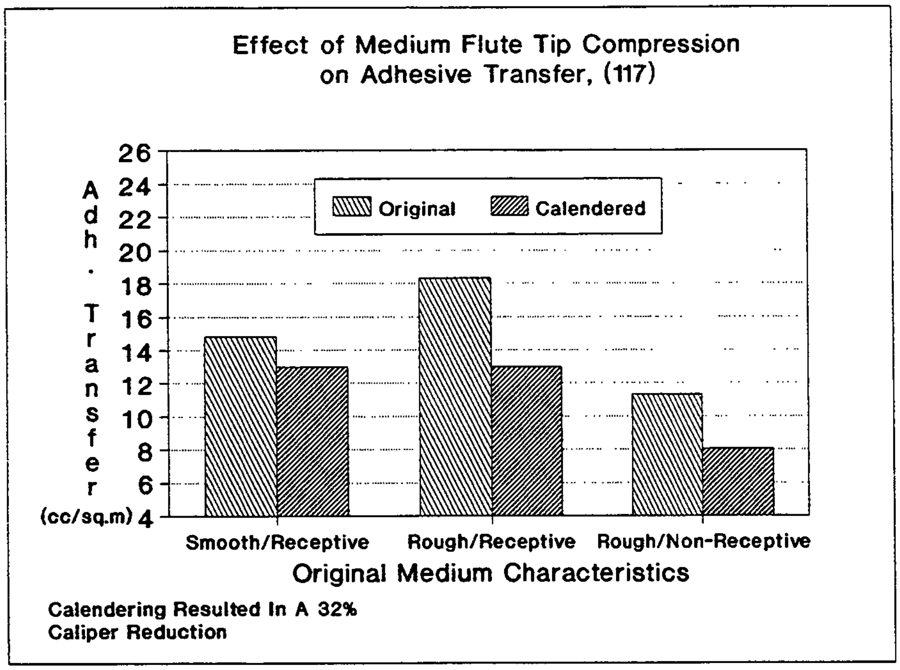
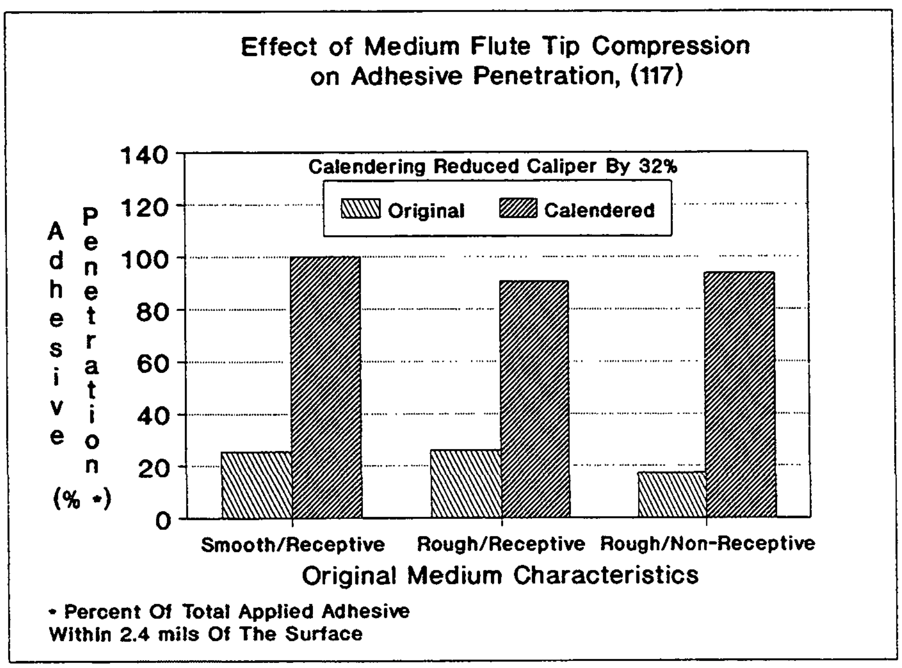


FIGURE 6.9
Effect of Medium Calendering on Adhesive Transfer and Penetration





sufficient water needed to gel the starch. The water is lacking in this area due to the mechanical dewatering caused by the pressure roll nip. This flute tip bond region has very little cured bond strength. It is thought, however, that this region provides some green-bond strength. The adhesive on the sidewalls of the flute do not contribute to the bonding since it is not in contact with the linerboard. The adhesive in the fillet zone is almost 100% gelled and provides the major portion of the total, cured bond strength, (18, 21, 35, 67, 76, 102).

Table 6.2. Adhesive Starch Penetration Into Medium in Commercially Corrugated Board, (14)

Distance Into Medium (mils)	Description of Starch Observed
0	Thick Surface Film
1	Abundant Starch
2	Few Starch Granules Visible
4	Trace of Solubilized Starch
6	No Starch

In summary, the formation of the corrugator bonds is a complex process. Obtaining uniformly strong and tough bonds requires the consideration of the following parameters. The influences of the linerboard facing material and the corrugator speed are not included.

1. The properties of the adhesive, particularly the solids content, gel point, and high-shear viscosity (not Stein-Hall viscosity).

2. The mechanical condition of the adhesive application system, particularly roll run-out and the tapered speed controls.

3. The properties of the medium, especially its receptivity to the adhesive slurry. This receptivity can be characterized by surface energy measurements.

4. The moisture content of the medium at the point in the process where the adhesive is applied.

5. The heat and pressure applied to the bond area.

6. The mechanical condition of the corrugator with respect to the shear and tensile forces transmitted to the green-bond areas.

Chapter 7

Single-Face Bonding

The quality of the single-face bond is important because of its potential effect on the box plant waste costs, on the box plant productivity, and on the performance of the corrugated package, (12, 14, 24, 47, 67, 71, 76, 79, 83). The development of the single-face bond is a complex process that involves the properties of the medium, the corrugating process conditions, and the mechanical condition of the corrugator, (20, 21, 22, 24, 35, 47, 67, 119, 148).

Some people have suggested that minimizing the consumption and cost of the starch adhesive should also be a top priority objective of the bonding process, (14, 71, 79, 83). The author takes exception to this philosophy. The starch adhesive is one of the least costly materials used in a box plant. The objective should be to control the bond strength at a high and uniform level, (47). The corrugator bond strength directly affects the compressive strength of the corrugated board. A 10% reduction in pin adhesion strength produces a 3.3% loss in the Edge Crush Test of the combined board and a 2.5% loss in top-to-bottom box compression, (5). It is the opinion of the author that an overabundance of adhesive should not be used because of its adverse effect on warp and other properties of the corrugated sheet, however, a miserly application rate should also not be used. Too little adhesive will increase the probability of waste and poor package performance. It is the author's opinion that trying to operate at single-facer dry adhesive application levels much below 1.0 lb/msf is penny-wise and dollar foolish.

The single-face corrugator bond begins its development the instant that the starch adhesive slurry is applied to the tip of the medium flute. The adhesive-covered flute tip is then brought into contact with the single-face linerboard web in the nip between the lower corrugating roll and the pressure roll. The bond exiting this nip must be of sufficient strength to hold the two paper webs together until the final, cured bond has formed. The bond site is not exposed to any additional heat or pressure until it enters the double-backer, (3, 8, 10).

The single-faced web is exposed to many shear and tensile forces during its trip to the double-backer. The web is exposed to flutter as it moves from the pressure roll nip, up the elevator, to the bridge. The web is then fan folded on itself as it enters the bridge and is pulled, with fits and starts, until it is unfolded at the web guide and enters the double-backer glue machine. All in all, it is a very bumpy ride. The single-face bond cannot be reformed if it separates due to these mechanical forces. Any such separation produces defects commonly called "blisters," "fluff-out," and "loose edges," (3, 8, 10).

The development of the single-face bond strength is a continuous process starting when the adhesive is applied and ending when the finished combined board leaves the corrugator and reaches temperature and moisture equilibrium with the ambient environment. The initial stages of the bond development, before significant fiber tear is detected, is commonly referred to as the "green-bond" stage. Once general fiber tear is observed, it is the practice to refer to it as the "cured" bond. However, as discussed in Chapter 6, the differentiation between the green-bond stage and the cured bond stage is not that simple. Fiber tear may be observed in the green-bond stage due to the wetting and disruption of the fiber-to-fiber bonds of the paperboard by the water present in the adhesive slurry. This is a "false" cured bond.

The objective of the single-face bonding process should be to obtain a balance between the two stages, (14). Neither a good green-bond strength that results in a corrugated product with a weak, brittle cured bond, nor a corrugated product with a strong, tough cured bond, but blistered areas due to a weak green-bond separation is acceptable.

The mechanisms involved in the development of the single-face bond are discussed in detail in Chapter 6. This chapter deals with the available technical information that relates the effect of the medium physical properties to the strength of the green-bond and cured bond stages. The effect of medium preconditioning is also included.

A typical green-bond strength development curve, observed for the initial stages of the bond forming process, is shown in ***Figure 7.1.*** The bonding time shown covers the range from 0 milliseconds to 200 milliseconds after the single-faced web has left the pressure roll nip. The green-bond strength was quantified by applying a mild, constant, mechanical stress to the edges of the web after it exited the pressure roll nip. The stress causes varying degrees of debonding to occur, originating at the edges of the web and extending toward the centerline of the web, depending on the strength of the green-bond. A strong green-bond results in no debonding. A very weak green-bond results in complete separation of the linerboard from the medium. Intermediate strength green-bonds result in varying degrees of separation. The experiments were conducted on a pilot-size corrugator, (3, 8, 10).

Figure 7.1 shows the bonded area plotted against the bonding time. The bonding curve can be characterized by four parameters. The induction time is the elapsed bonding time before any measurable bond strength is detected by the methods used in this study. This does not imply that there is no bond strength at all during this time interval, only that any bond strength that exists is too weak to resist the mild mechanical force that was applied to the web. Once a measurable bond develops, the strength of the bond increases linearly with time. The slope of this linear section of the bonding curve is called the bonding rate. The induction time and the bonding rate can be combined to produce a calculated minimum time to a 100% bond. The bonding time in these experiments was varied by changing the corrugator speed. The decrease in the observed bond strength in some samples, after the maximum was reached, is attributed to the overheating and crystallization of the starch adhesive at the slower corrugator speed, (3, 8, 10). The green-bond strength development is improved by a shorter induction time and a higher bonding rate.

Figure 7.2 shows the measured induction time, bonding rate, and calculated time to 100% bond for the 15 commercial mediums evaluated. The mediums included NSSC, Caustic Carbonate, Green Liquor, and Recycled materials. The green-bond development characteristics were measured for each medium at two different medium preconditioning levels, normal and reduced. The data show a relatively wide variability in green-bond strength development for the 15 mediums under reduced preconditioning levels. Increasing the preconditioning level to normal reduced the induction time by an average of 16%, increased the bonding rate by an average of 47%, and decreased the calculated time to 100% bond by an average of 26%. The added preconditioning also reduced the magnitude of the differences in green-bond development observed between the different medium materials.

These results show that the use of proper medium preconditioning levels can overcome most of the effect of differences in the medium material properties on the green-bond strength development. This emphasizes the importance of the proper maintenance and proper utilization of the medium preheaters and steam showers in the single-facer process. This is especially true during speed changes on the corrugator. The preconditioning should be reduced simultaneously with reducing the corrugator speed and increased simultaneously with increasing speed, (8, 10).

The green-bond strength measurement technique described above was used to determine the relative effect of the medium and linerboard moisture contents, the medium and linerboard temperatures, and the bonding time on the green-bond strength development. The medium web's temperature and moisture content were measured with sensors located as close as possible to the in-feed side of the corrugating rolls. The bonding time was varied by maintaining a constant corrugator speed and moving the debonding stress device to different distances from the pressure roll nip, (3).

Figure 7.3 shows the multiple regression equation relating the green-bond strength, as indicated by the percent bonded area, to the variables of moisture content, temperature, and time. The effect of all five variables was statistically significant at greater than the 99% probability level. The equation constants indicate that the medium moisture content has more of an effect than the medium temperature. However, this is an artifact of the difference in the numerical values of the two variables. The absolute numerical value for the medium temperature is about 25 times the numerical value of the medium moisture content, 188 deg.F. versus 5.5% MC. ***Figure 7.4*** shows the relative impact of the five variables based on a constant 10% change in the variable. On this basis, the medium temperature has approximately three times more of an effect than the medium moisture content, and the bonding time has approximately twice the effect of the medium moisture content, (3)

Figure 7.5 shows a regression equation which relates the cured bond pin adhesion to a number of medium properties and single-facer process conditions. The equation contains 11 terms, all of which were found to be statistically significant at the 95% or greater probability level. The equation contains interactive terms which make a direct comparison of the relative effect of each variable difficult to quantify. In general, however, the data indicate that the cured bond pin adhesion strength increases as corrugator speed decreases, as the medium nip temperature decreases, and as the nip moisture content increases, (16).

Figures 7.6 and 7.7 show that the cured bond pin

FIGURE 7.1

SF Green-Bond Development Curve. (8, 10)

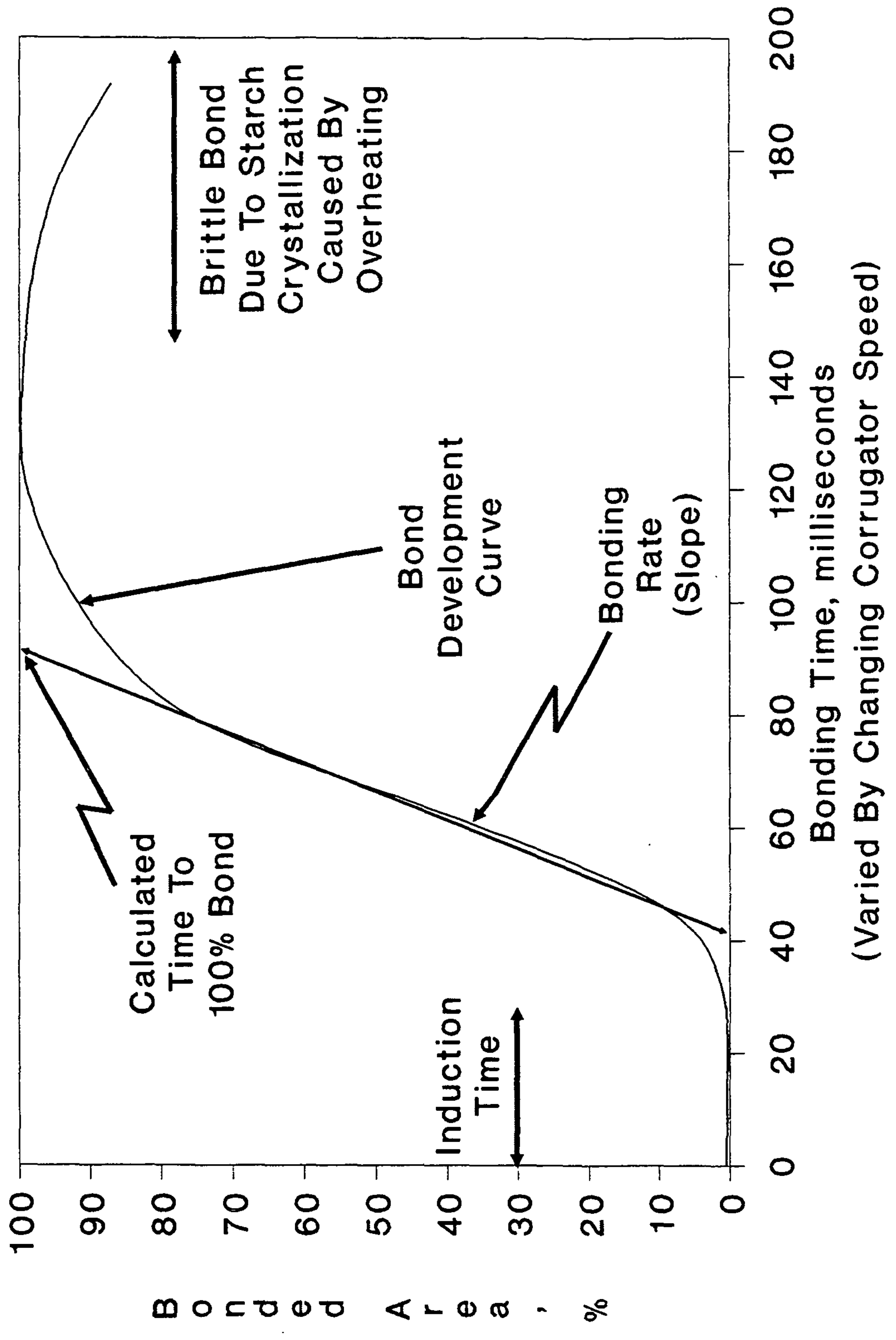


FIGURE 7.2
Effect of Medium Preconditioning on Green-Bond Development

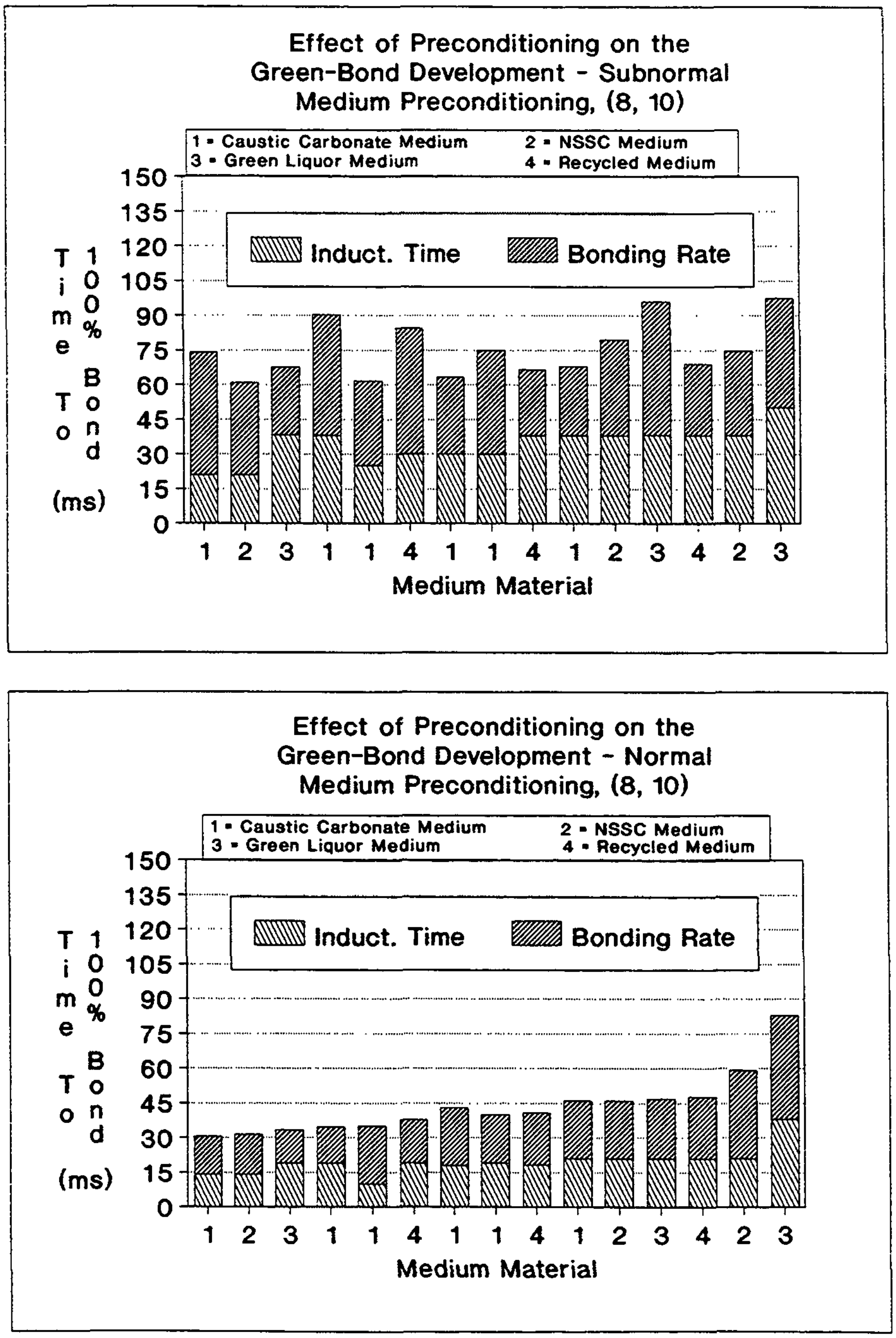


FIGURE 7.3

Effect of Corrugating Variables on Single-Facer Green-Bond Development

$$\text{Bond} = a(A) + b(B) + c(C) + d(D) + e(E) - 257.7$$

$$r^2 = 0.806$$

Bond = Percent Bonded Area

a = 0.461	A = Linerboard Temperature, Deg.F
b = 0.544	B = Medium temperature, deg.F
c = 3.94	C = Linerboard Moisture Content, %
d = 6.06	D = Medium Moisture Content, %
e = 0.474	E = Bonding Time, millisec.

FIGURE 7.4
Single-Facer Green-Bond Development
Sensitivity to Process Conditions, (3)

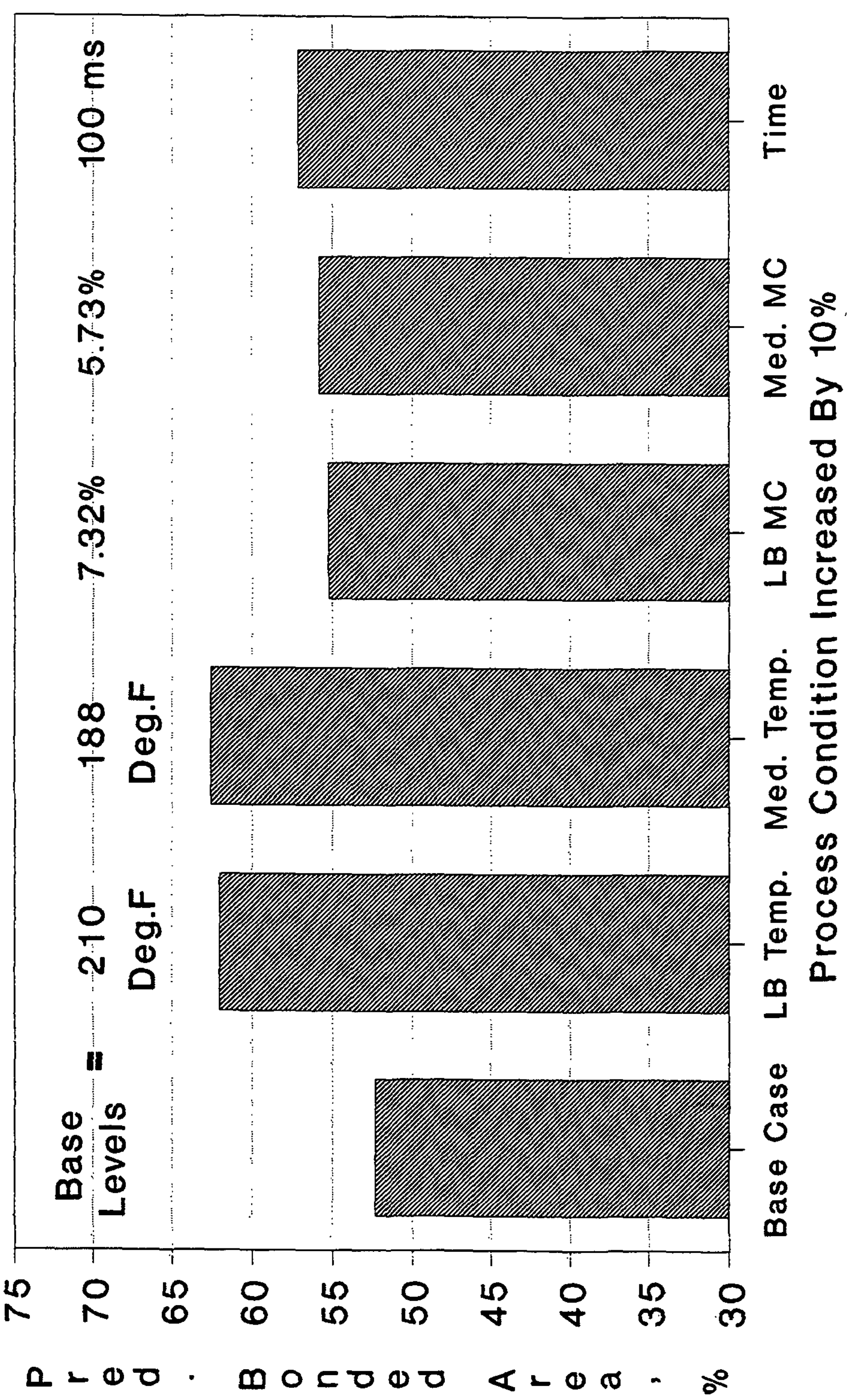


FIGURE 7.5
Effect of Corrugating Conditions and Medium Properties on Cured Pin Adhesion, (16)

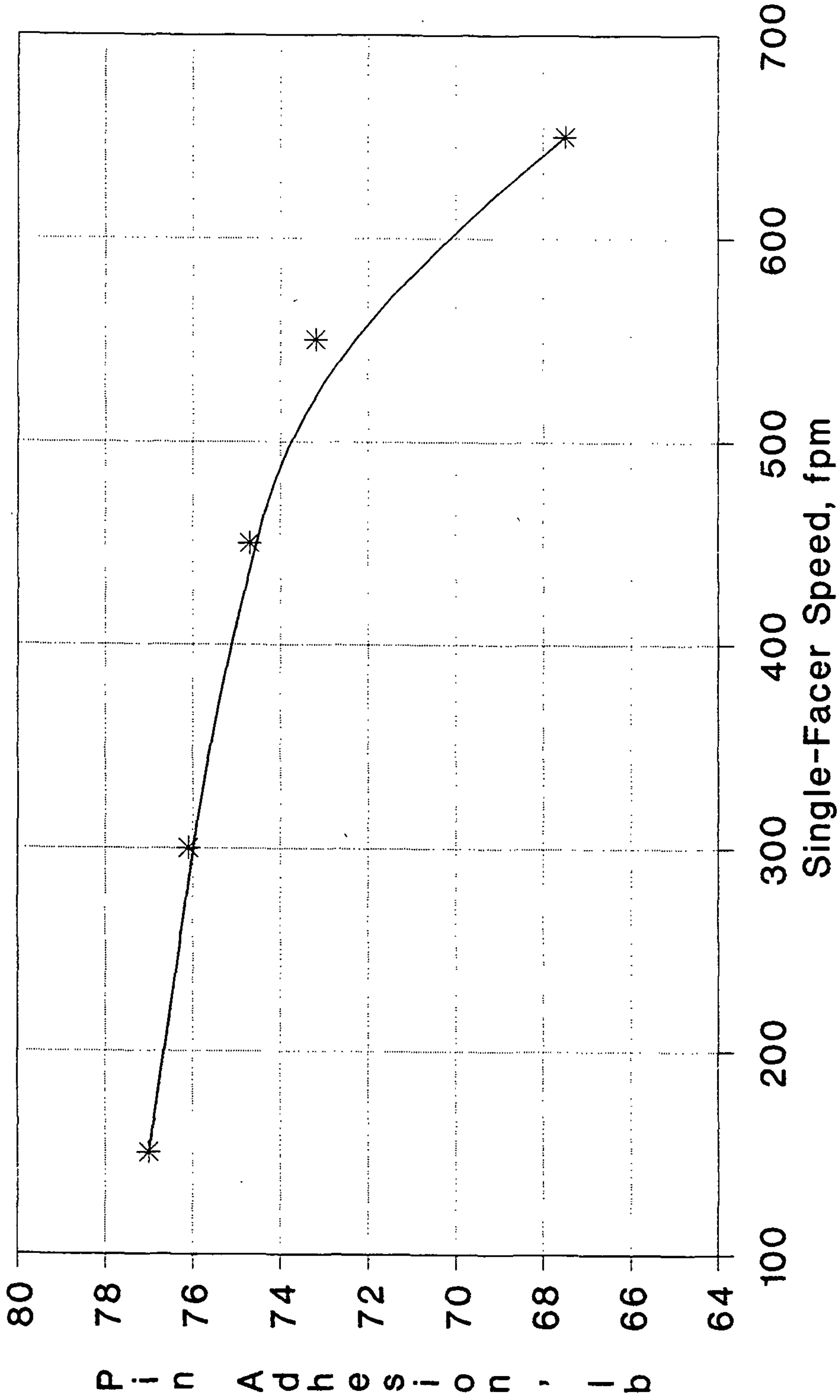
$$PA = 110.6 - a(A) - b(B)^3 - c(C)^2 + d(D) - e(E) + f(F) - g(G) - h(H) + i(I)^2 + j(J) - k(K)^2 + l(L)$$

$$r^2 = 0.89$$

PA = Cured Pin Adhesion, psi

a = 20.1	A = Speed/100, fpm
b = 0.0439	B = A
c = 10.0	C = Medium Nip Temperature/100, Deg.F
d = 11.7	D = A times C
e = 36.3	E = Water Drop/100, sec.
f = 9.34	F = E times Soft Platen Density (lb/msf per mil)
g = 0.888	G = Gurley Porosity, sec.
h = 251	H = Soft Platen Density minus Hard Platen Density
i = 185	I = H
j = 4.14	J = Medium Nip Moisture Content, %
k = 0.155	K = J
l = 3.87	L = Medium Basis Weight, lb/msf

FIGURE 7.6
Effect of Single-Facer Speed on
Single-Face Cured Pin Adhesion. (119)



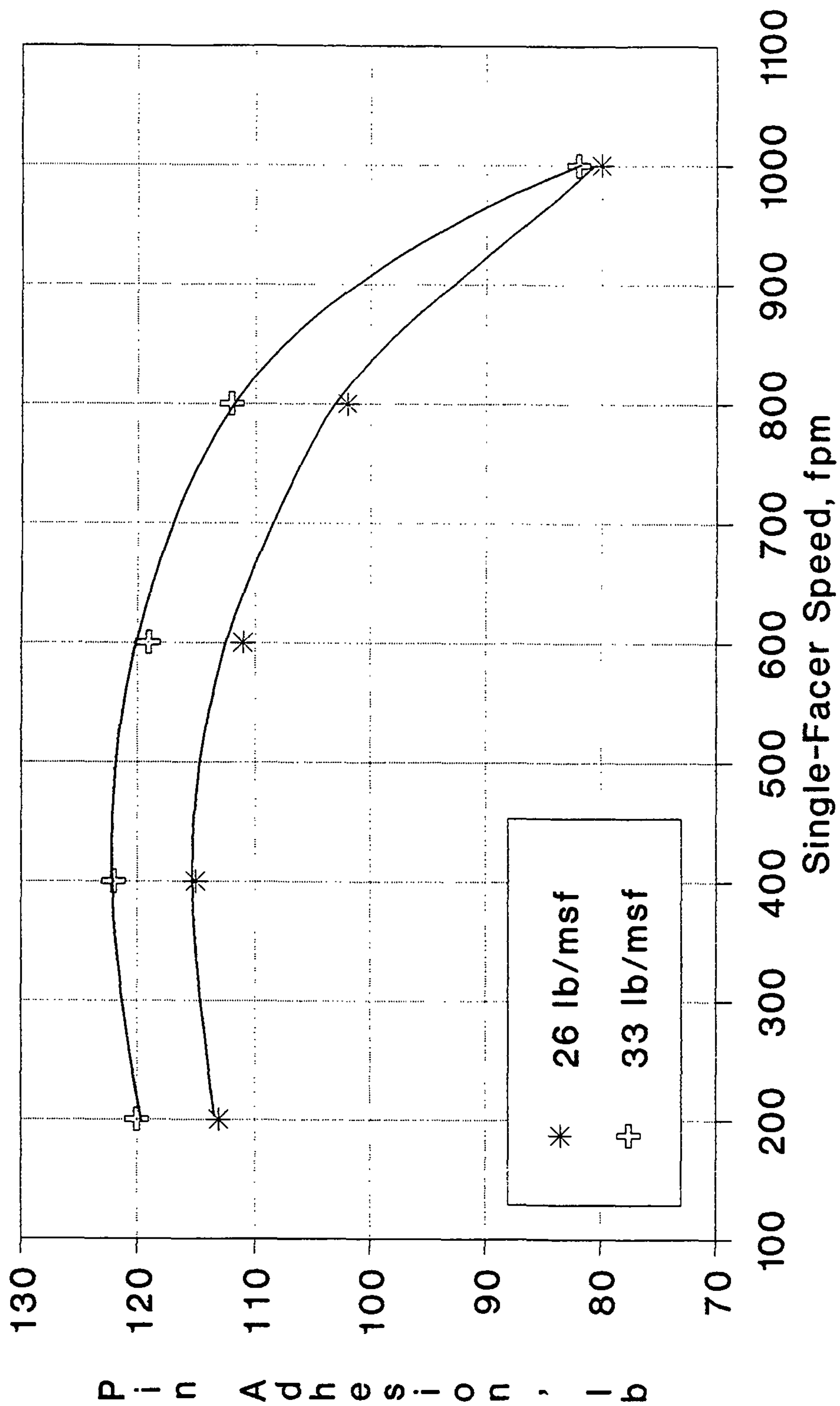


FIGURE 7.7
Effect of Single-Facer Speed and Medium Basis Weight on Cured Pin Adhesion. (17)

adhesion strength decreases with increasing corrugator speed. The studies were conducted on a pilot-size single-facer, (17, 119). These results confirm the speed effect predicted by the regression equation shown in ***Figure 7.5***. ***Figure 7.8*** shows that the cured pin adhesion strength decreases with decreasing adhesive application, (14, 58, 120). It may be hypothesized that the observed decrease in cured bond pin adhesion with increasing speed is due to a lower adhesive application rate at the higher speed. The effect of speed on the adhesive film thickness on the applicator roll is discussed in Chapter 6. ***Figure 7.9*** shows the results of a study which measured both the cured pin adhesion strength and the adhesive application rate as a function of the corrugator speed. The experiment was conducted on a pilot-size corrugator. The data show a direct correlation between the pin adhesion strength and the amount of applied adhesive in the corrugator speed range of 200 to 400 fpm. Above the 400 fpm speed, the pin adhesion strength continued to decrease while the adhesive application rate increased, (85). This behavior would suggest that the adverse effect of the faster corrugating speed on the cured bond strength is, in part, related to a reduction in the amount of adhesive applied, but also may be due to the increased mechanical stresses on the green-bond at the faster speeds.

Figure 7.10 shows the effect of the medium water drop test property on the cured bond pin adhesion strength. The data indicate that there is an optimum range for the water drop property. It would appear that a medium that is neither extremely absorbent nor extremely nonreceptive will achieve the strongest cured bond, (104). There is some controversy about the merits of the water drop test as an indicator of medium quality, (85).

The effect of medium preconditioning at the single-facer on both the green-bond strength and the cured bond strength is shown in ***Figure 7.11.*** Using less than normal preconditioning for the medium web reduced the green-bond strength development by 53%, but had only a 3% negative effect on the cured bond strength, (8, 10). This indicates that the medium preconditioning should be set so as to maximize the green-bond development. The medium preconditioning should not be adjusted, as so often happens, based on observation of the cured or "false" cured bond at the dry end of the corrugator.

In summary, the experimental data presented in this chapter support the following observations.

1. The green-bond strength development, within 200 milliseconds after the single-faced web leaves the pressure roll nip, is affected primarily by the temperature and moisture content of the medium web entering the corrugating rolls. A higher medium temperature and a higher medium moisture content favor quicker green-bond strength development.

2. Medium material properties appear to have only a second-order effect on the green-bond strength development when adequate medium preconditioning is used. A more porous medium and a less wettable medium favor a quicker green-bond strength development.

3. The cured bond strength is related mainly to the amount of adhesive applied, and to the receptivity of the medium to wetting by the starch adhesive. The medium should be neither extremely absorbent nor extremely nonreceptive.

4. The temperature and moisture content of the medium entering the corrugating rolls are secondary effects for the cured bond strength. The cured bond strength is improved by a lower medium temperature and a higher medium moisture content.

5. Faster corrugator speeds are detrimental to both the green-bond and the cured bond strength. The speed effect appears to be associated with a reduced adhesive transfer to the medium flute tip and with the increased mechanical stress on the green-bond.

6. The single-facer medium preconditioning should be controlled primarily to enhance the green-bond formation. Preconditioning should be increased simultaneously with corrugator speed increases and should be reduced when the corrugator speed is slowed.

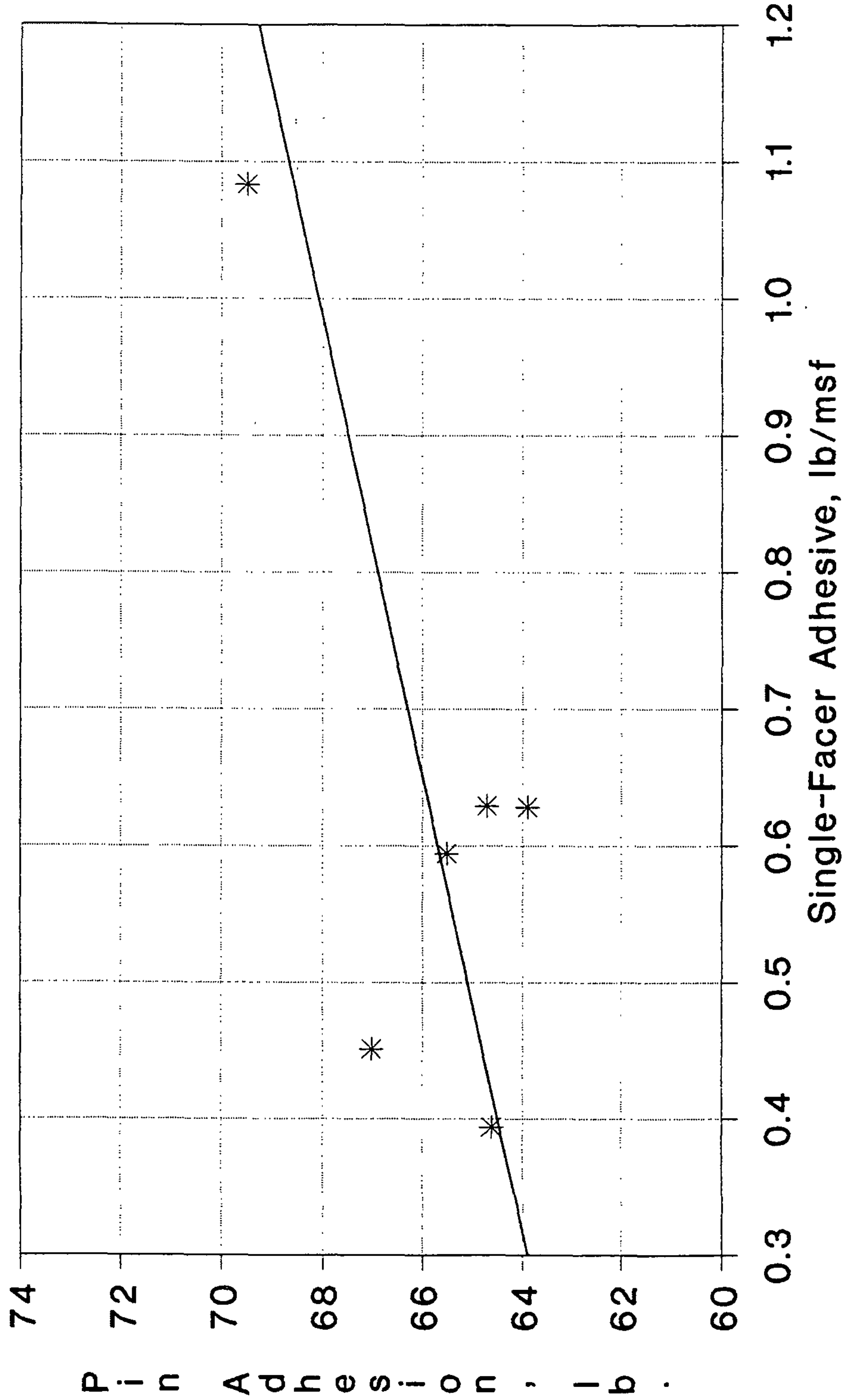


FIGURE 7.8
Effect of Adhesive Application on Cured Pin Adhesion, (71, 79, 83)

FIGURE 7.9

Effect of Speed on Cured Pin Adhesion and Dry Adhesive Application Level. (85)

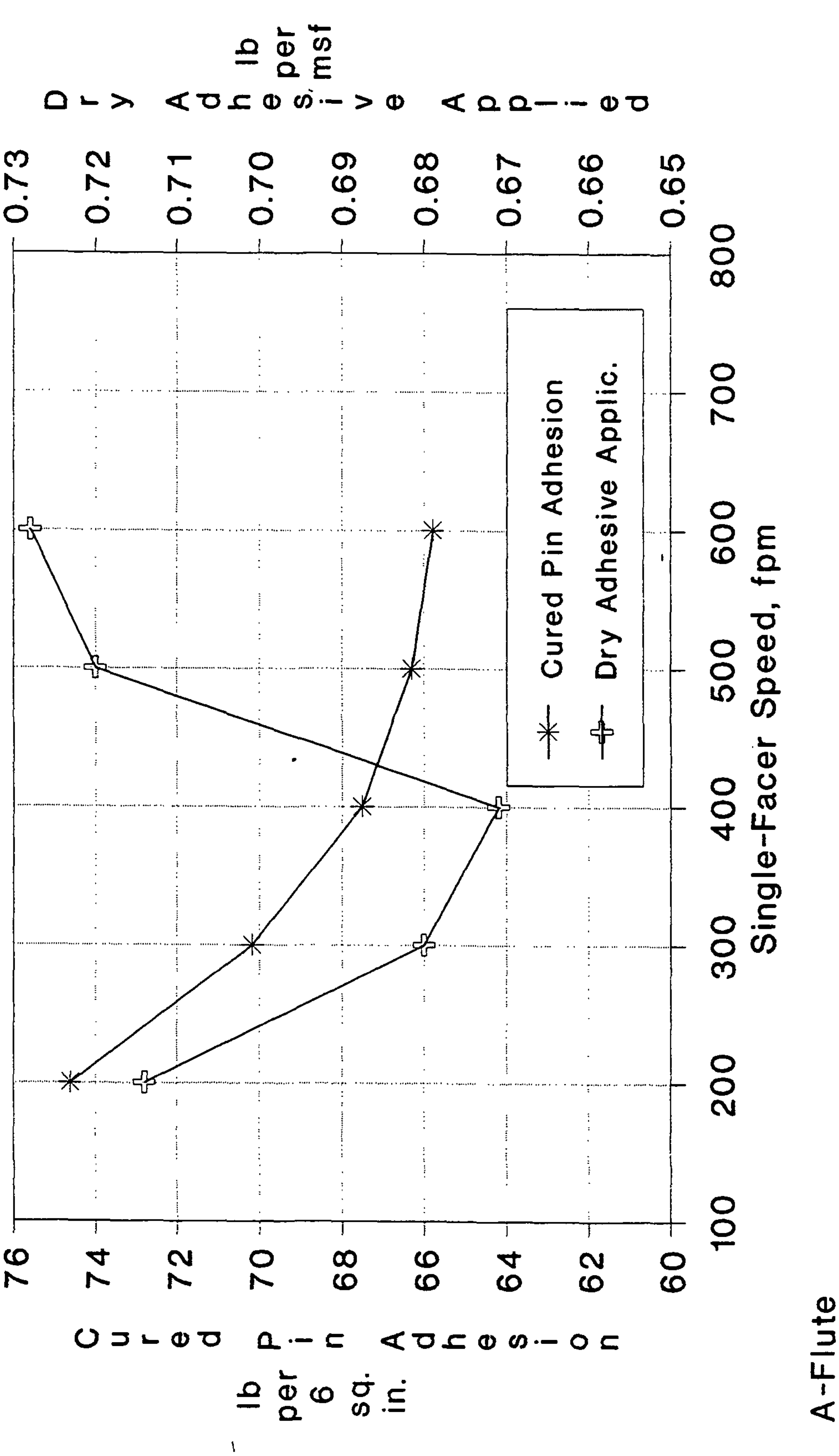


FIGURE 7.10
Effect of Medium Water Drop Test on Cured Pin Adhesion, (104)

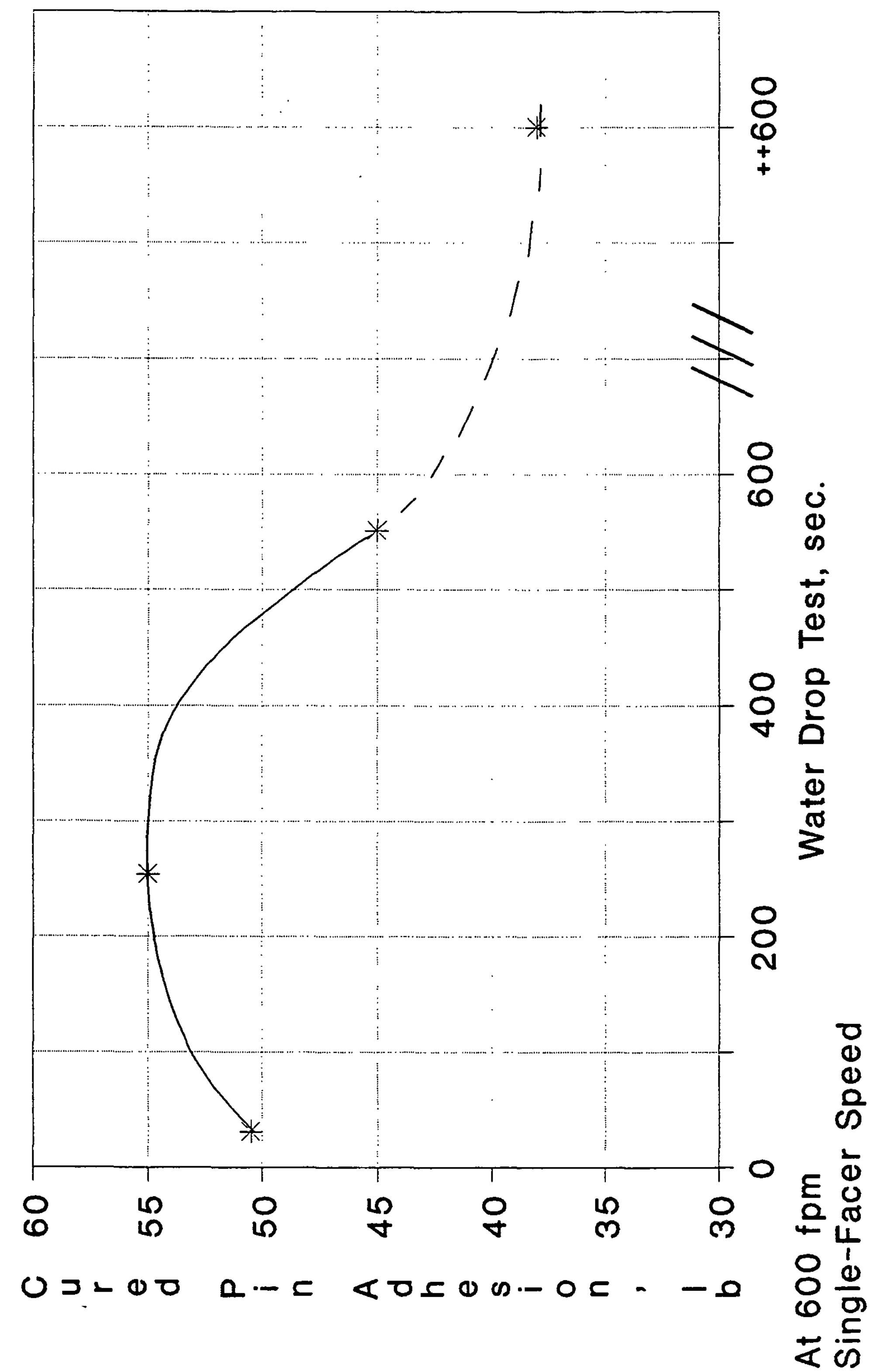
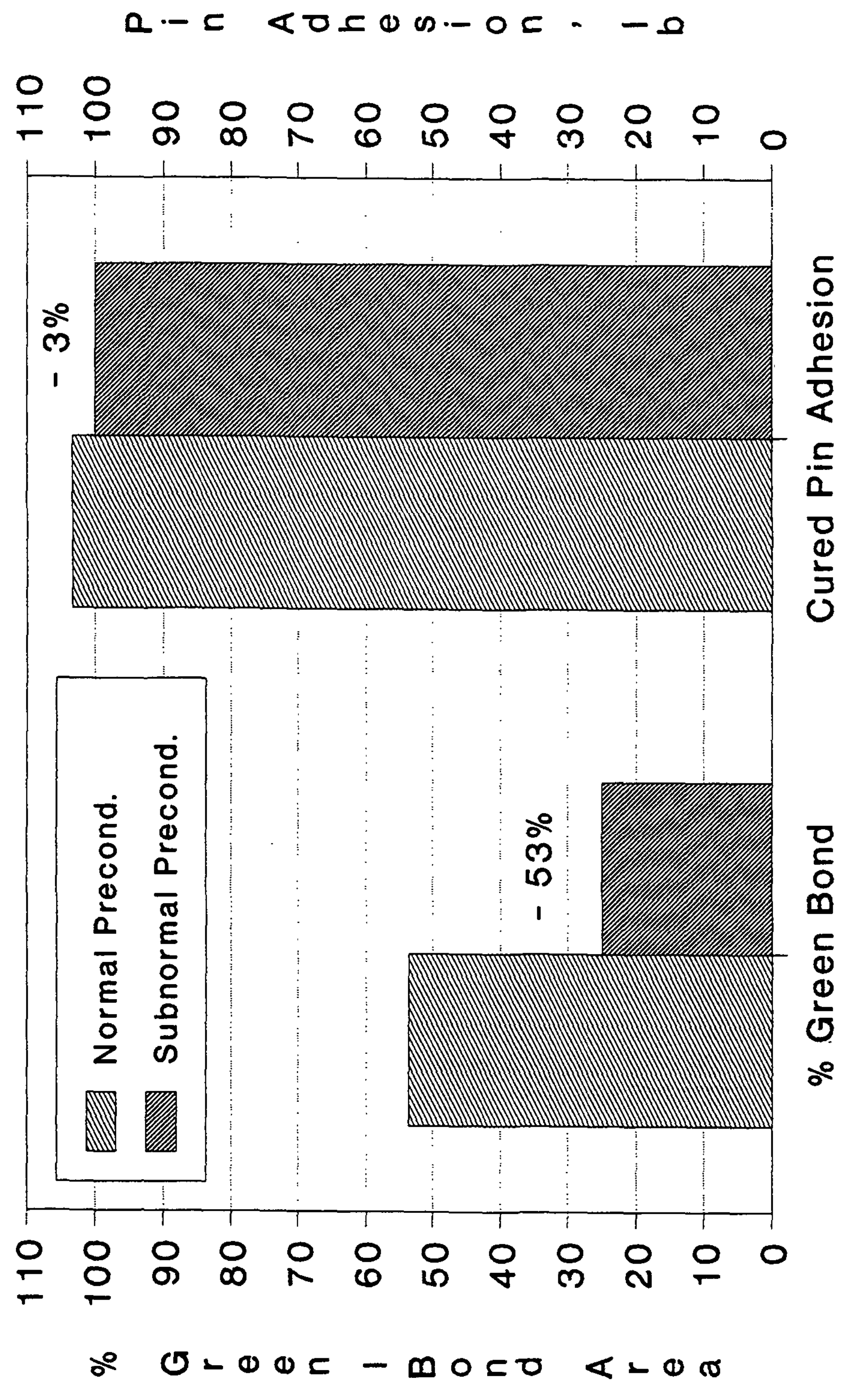


FIGURE 7.11
Effect of Preconditioning on SF Green-Bond and Cured Bond. (10)



Chapter 8

Double-Face Bonding

As was stated in Chapter 7 for the single-face bond, the double-face bond is important because of its potential impact on the box plant waste costs, on the box plant productivity issues, and on the functional performance of the corrugated paperboard package, (12, 13, 14, 24, 47, 67, 71, 76, 79, 83). The double-face green-bond development rate is the factor that generally governs the speed of the corrugator. The double-face green-bond must be strong enough to pass through the corrugator slitter/scorer unit and the cut-off knife without causing permanent bond separation in those areas of the board where the forces are applied. It is generally felt that the final, cured double-face bond will form in the board stacks under the pressure of the sheet weight, (12, 18). The cured bond strength directly affects the Edge Crush Test strength of the corrugated board and the compressive strength of the corrugated box. A 10% reduction in the cured pin adhesion strength of the double-face bond will cause a 3.3% reduction in the Edge Crush Test and a 2.5% loss in top-to-bottom box compression.

The double-face bond formation process is somewhat simpler than that for the single-face bond formation process. Experiments and experience have shown that the physical properties, varying over a wide range, of the corrugating medium do not play a major role in the development of the double-face green-bond. The green-bond formation is controlled mainly by the rate of heat conduction to the double-face bond site. Higher hot plate temperatures, lower gel point adhesives, and thinner double-face linerboard materials all improve the rate of double-face green-bond formation, (12, 24, 71, 79, 83). Other process variables which influence the double-face green-bond rate of formation include adhesive viscosity, adhesive solids, adhesive application rate, adhesive slurry temperature, preheating of the double-face linerboard and the single-faced web, and the pressure applied in the double-backer hot plate section, (24).

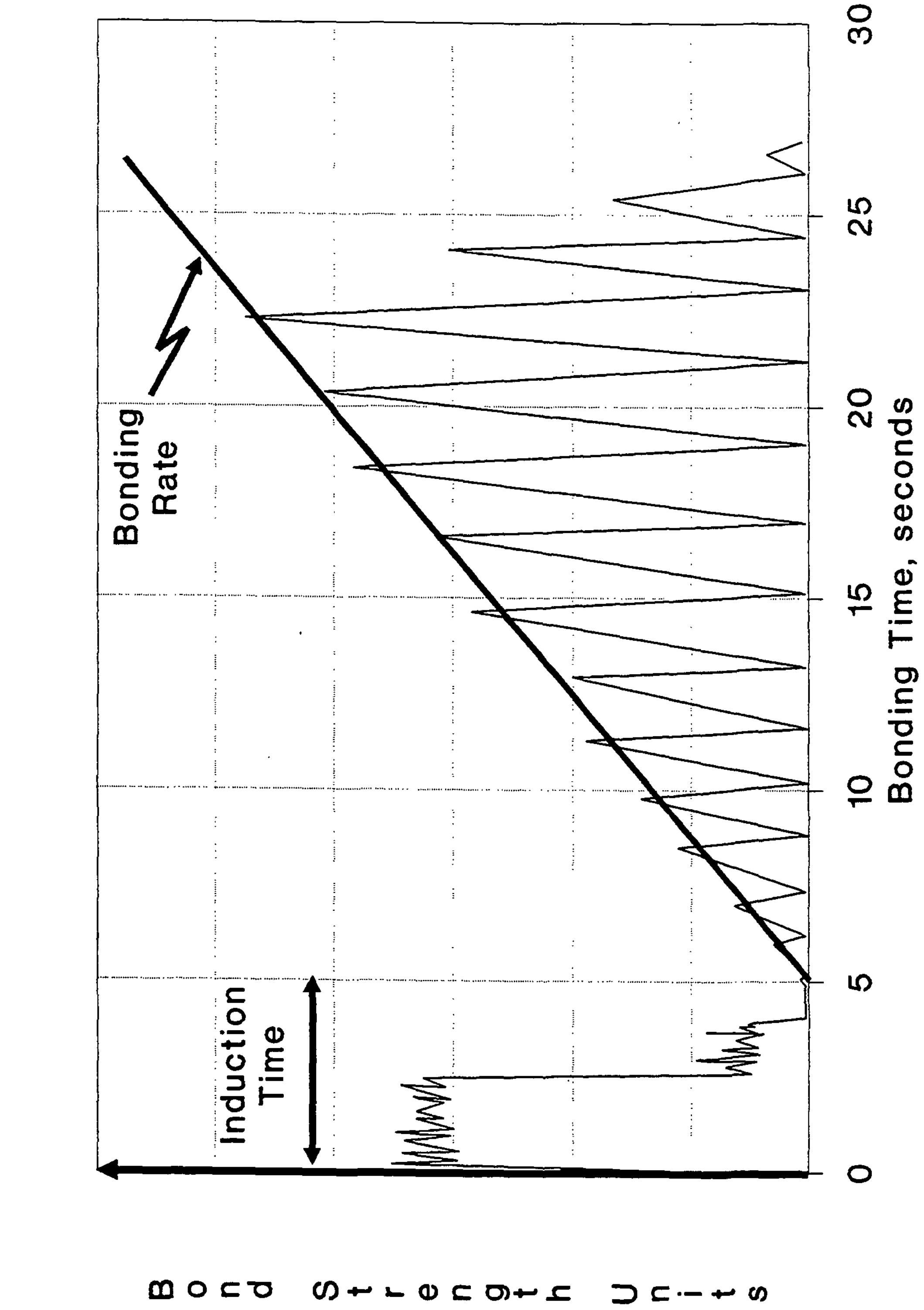
The double-face bonded area exhibits three major zones. The adhesive on the exterior sides of the flute contains both gelled and ungelled (raw granules) starch. This zone does not contribute to the bond strength since the adhesive does not contact the linerboard facing. The fillet area is where the adhesive has been squeezed out and fills the angle between the fluted medium and the linerboard. This zone contains almost 100% gelled starch. The contribution of the fillet zone to bond strength can vary. It often contains void spaces that reduce its bonding effectiveness. The high bonding zone is where the adhesive is in intimate contact with both the medium and the linerboard and where the starch is fully cooked and gelled. This zone provides the preponderance of the bond strength, (13, 18, 67, 76).

The details on the mechanisms involved in the development of the corrugator starch slurry into an adhesive were discussed in Chapter 6. They will not be repeated in this chapter.

A schematic representation of strength development in a typical double-face bond is shown in ***Figure 8.1.*** The data were generated using a double-backer simulator developed at the Institute of Paper Science and Technology. The simulator can reproduce the temperatures, pressures, adhesives, adhesive application rates, and speeds attained in full-size commercial corrugator operations. It is also equipped with a stress gauge that can measure the bond strength of each double-face glue line leaving the double-backer hot plate section, (13, 18, 24).

The double-face bond strength development curve, ***Figure 8.1*** is similar in nature to the single-face green-bond development curve shown in ***Figure 7.1*** of Chapter 7. They both have induction times, during which no measurable bond strength occurs; a linear bond strength increase with time (bonding rate), once the bond has started to form; a maximum bond strength; and a drop off in bond strength after the maximum strength has been achieved. The most significant difference between the two bonding curves is the magnitude of the times involved. The typical single-face induction time was about 20 milliseconds. The

FIGURE 8.1
Double-Face Bond Development Curve. (24)



typical double-face induction time is 5 seconds, a 250-fold increase. The typical single-face bonding rate is 7.1 percent bond per millisecond. The typical double-face bonding rate is 5.7 percent bond per second, a 1250 fold decrease. Some of these difference may be attributed to the effect of the pressure roll nip and heated corrugating rolls in the single-facer process. However, the interpretations of the physical events, occurring at the various stages, also differ.

The indicated measurable bond strength in the induction time stage is not a true experimental bond strength but an artifact of the experimental technique. The bonding rate stage represents the viscosity increase and setting of the starch base adhesive. The saw-tooth shape of the bond strength curve is caused by the alternation of flute tips (plot peaks) and between flute tip areas (plot valleys) passing the stress gauge. The maximum bond strength represents the point at which linerboard fiber tear occurs. This probably is not the cured bond strength since the linerboard would have a high moisture content at the bond site due to the water associated with the adhesive slurry. The high linerboard moisture content disrupts the fiber-to-fiber bonding and lowers the force required to produce fiber tear. The decrease in bond strength after the maximum strength has been reached is not a true physical occurrence. It is an artifact of the termination of the experimental test, (13, 18, 24).

Improvement in the double-face green-bond development process is achieved by reducing the induction time stage and by increasing the bonding rate. The double-face cured bond strength, assuming no brittle "zipper" bond, will be governed by the ZD (thickness direction) fiber-to-fiber bond strength of the linerboard, (13, 18).

Figure 8.2 shows the double-face green bond strength as a function of bonding time. The data represent the results of laboratory experiments. As shown in the previous figure, the bond strength increases linearly with time. The bond rate development shown by the data is 29.7 mJ per second, (12).

Figure 8.3 shows the effect of the hot plate temperature on the bonding time required to achieve linerboard fiber tear at the bond sites. The data show that the bonding time required decreases as the hot plate temperature increases and as the double-face linerboard basis weight decreases. The bonding time to fiber pull failure is 0.135 seconds per lb/msf linerboard basis weight at a hot plate temperature of 250 deg.F., and 0.066 seconds per lb/msf linerboard basis weight at a hot plate temperature of 350 deg.F., (71, 79, 83). These data support the previous observations which indicated that the double-face bond development is primarily controlled by the speed with which heat is conducted to the bond site.

Figure 8.4 shows the calculated effect of the double-face green-bond induction time on the maximum achievable corrugator speed. The calculation indicates that an induction time of 5 seconds or less is required to achieve the fastest design speeds of the current new corrugators, (24).

The effect of the hot plate temperature and the adhesive slurry temperature on the double-face green-bond induction time is shown in ***Figure 8.5.*** The data were developed using the previously described double-backer simulator. The experimental data show that the induction time is decreased by higher hot plate temperatures and by higher adhesive slurry temperatures. The average magnitude of the hot plate temperature effect on the induction time is 0.162 seconds/deg.F. The average magnitude of the adhesive slurry temperature effect on the induction time is 0.081 seconds/deg.F., (18).

The effect of the hot plate temperature and the adhesive slurry temperature on the double-face green-bond bonding rate is shown in ***Figure 8.6.*** The data were developed using the previously described double-backer simulator. The experimental data show that the bonding rate is increased by higher hot plate temperatures and by higher adhesive slurry temperatures. The average magnitude of the hot plate temperature effect on the bonding rate is 0.0073 lb/sec. per deg.F. The average magnitude of the adhesive slurry temperature effect on the bonding rate is 0.0027 lb/sec. per deg.F., (18).

Figure 8.7 shows the effect of the adhesive slurry gel point on the bonding time required to achieve a bond strength of 150 mJ and 300 mJ. The experimentation was done on a modified Strohlein apparatus which was originally developed for testing gummed tape. The data show that the bond strength development time is reduced by decreasing the adhesive slurry gel point. The data show that the effect reaches a minimum plateau at a gel point of 51 deg.C., below which no further bond development improvement occurred, (12). The gel point must also be controlled so as to maintain the stability of the adhesive slurry in the glue pan. Too low a gel point could cause premature gelling of the adhesive in the adhesive application equipment.

Figure 8.8 shows the effect of contact time with the preheater on the double-face green-bond induction time and bonding rate. Increased preheater contact time translates into a higher single-faced web temperature at the time the adhesive is applied to the flute tips, and a higher double-face linerboard web temperature at the time that contact is made between the double-face linerboard and the single-faced web flute tips. Longer preheater contact time (higher web temperature) decreases the induction time and increases the bonding rate, (13).

As was stated at the beginning of this chapter, the

FIGURE 8.2

Effect of Bonding Time on the Double-Face Green-Bond Strength, (12)

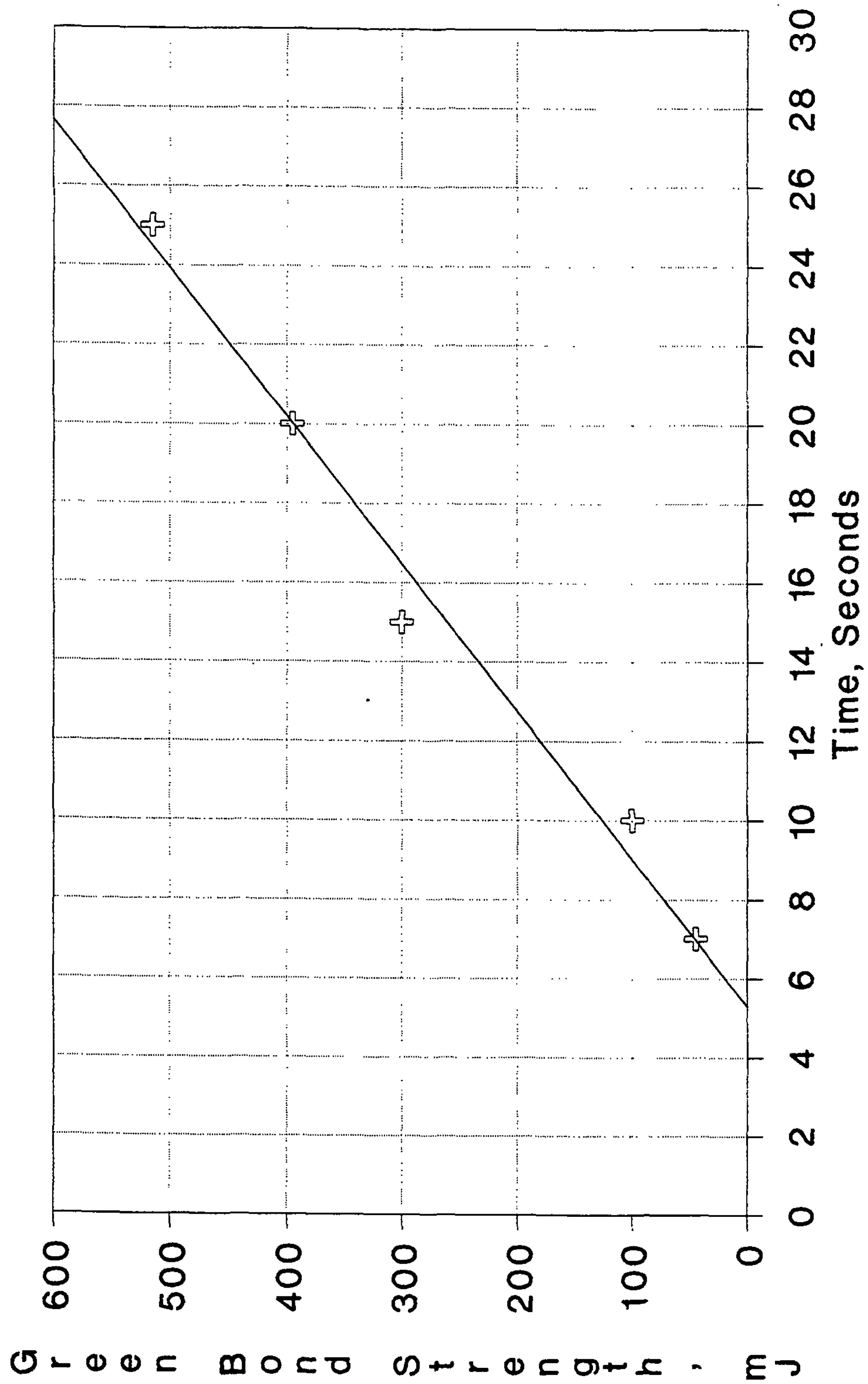


FIGURE 8.3

Relation of Bonding Time and Hot Plate Temperature at Linerboard Fiber Pull Stage of Double-Face Bond Development. (71, 79, 83)

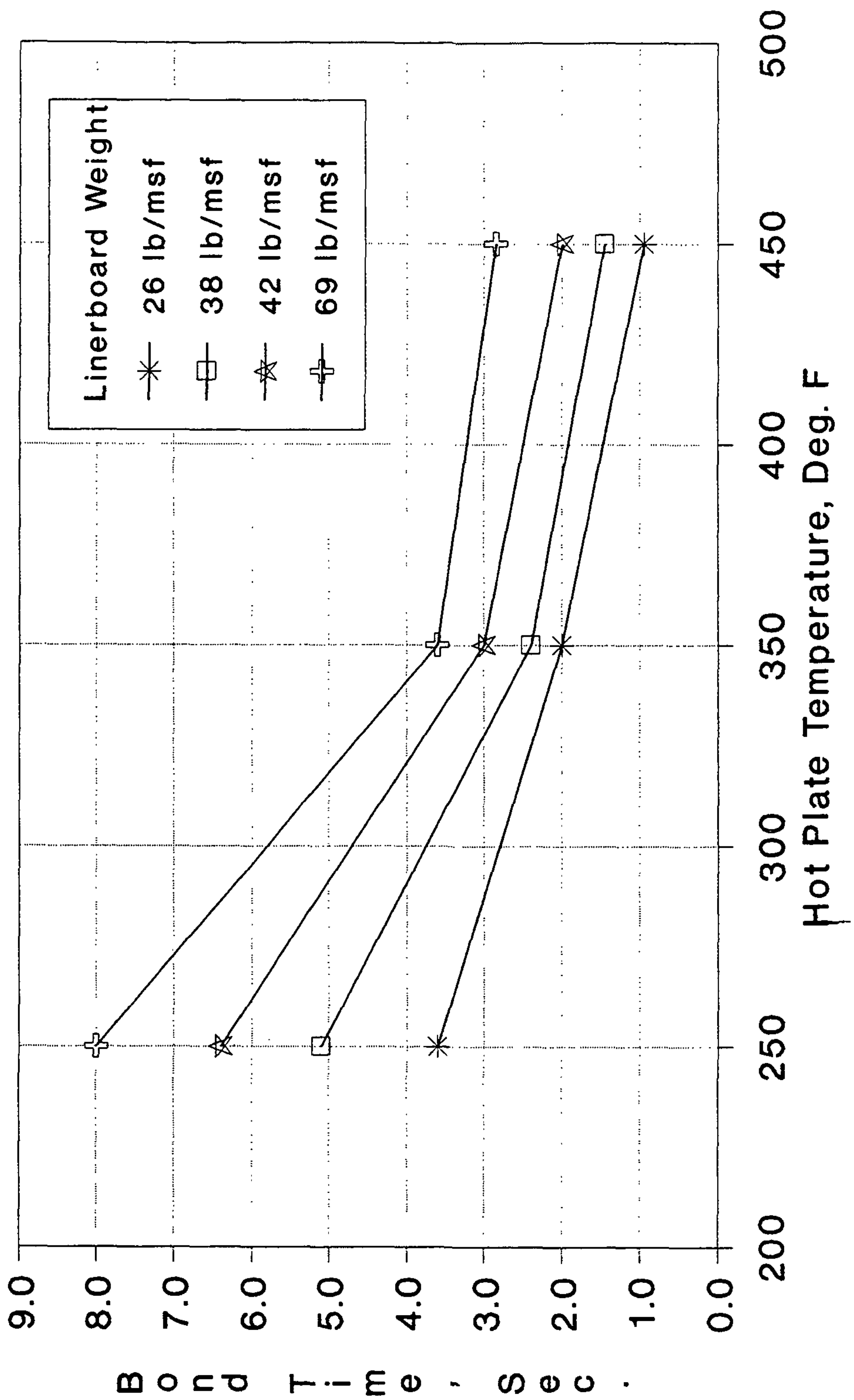
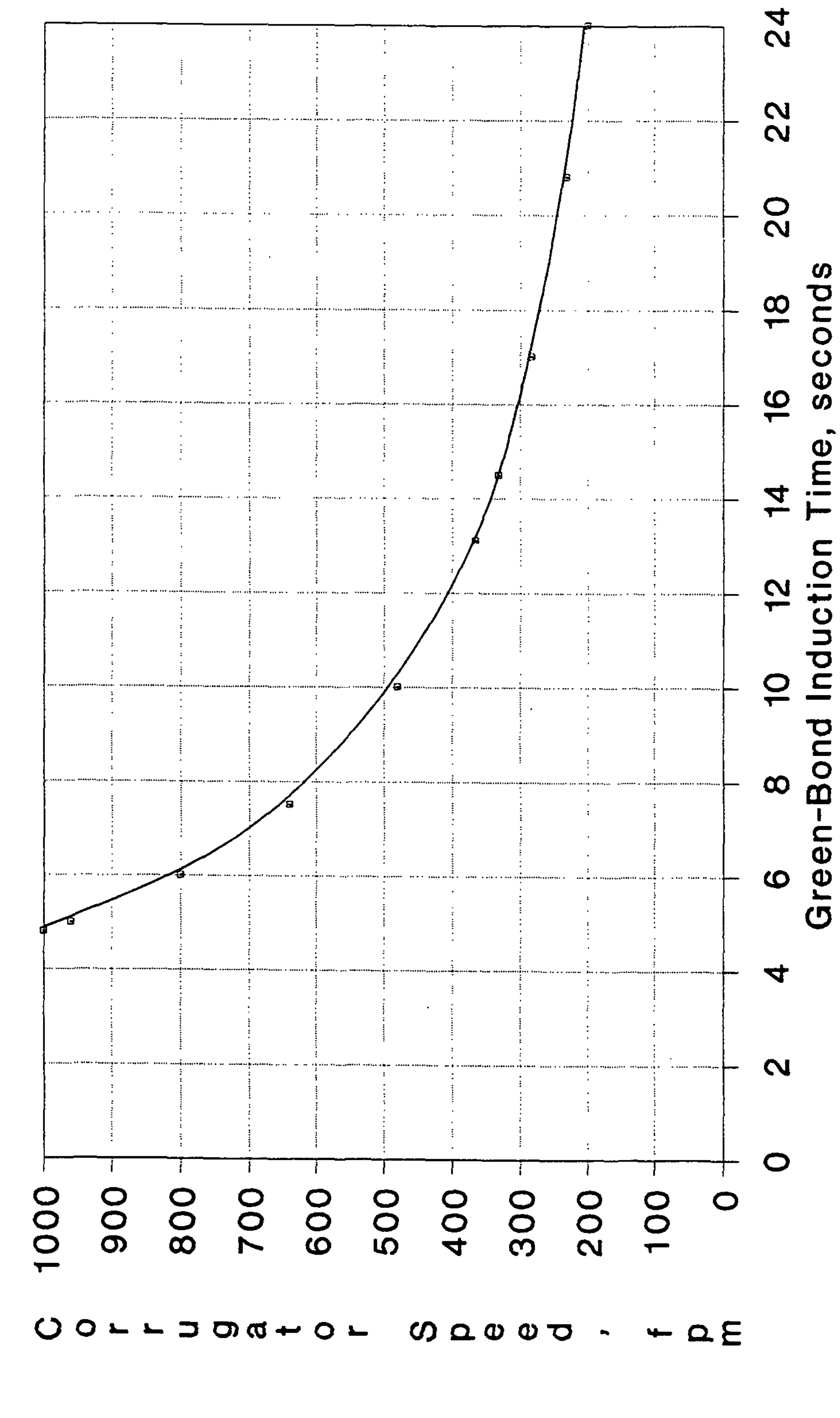


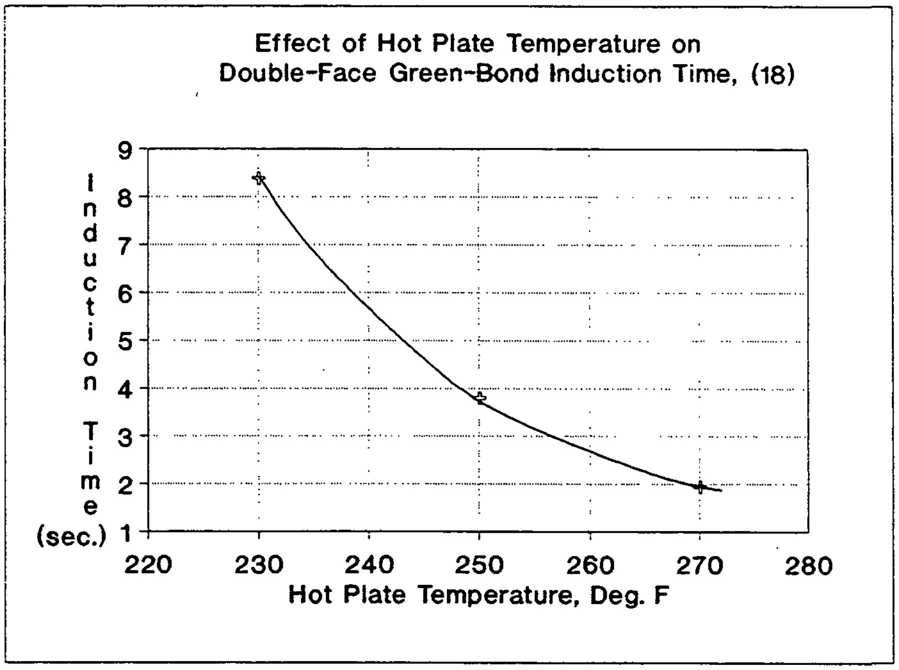
FIGURE 8.4
Effect of Double-Face Green-Bond Induction Time on Corrugator Speed. (24)



Calculated Speed Values.

FIGURE 8.5

Effect of Hot Plate and Adhesive Temperature on Double-Face Green-Bond Induction Time



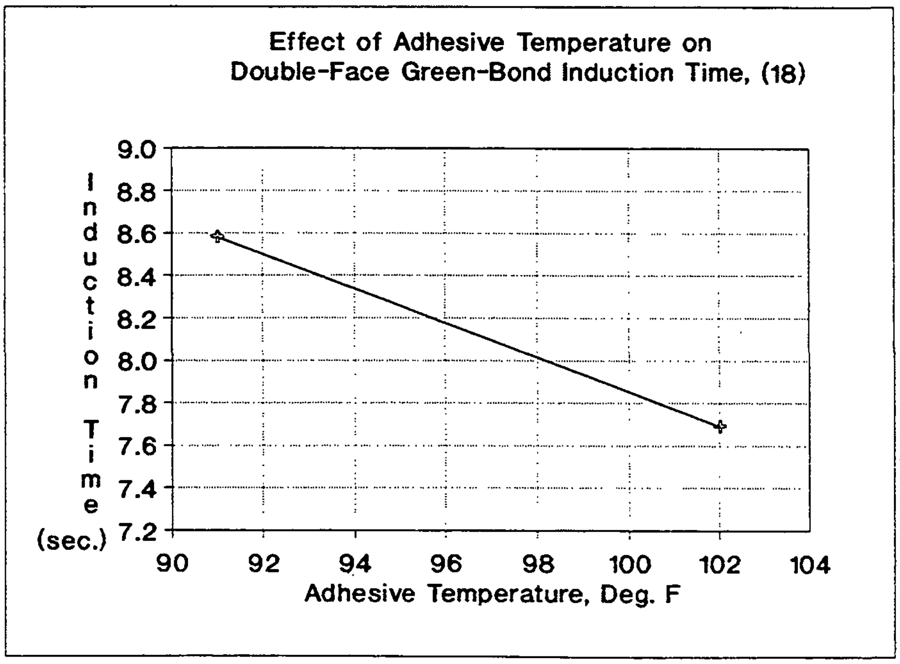
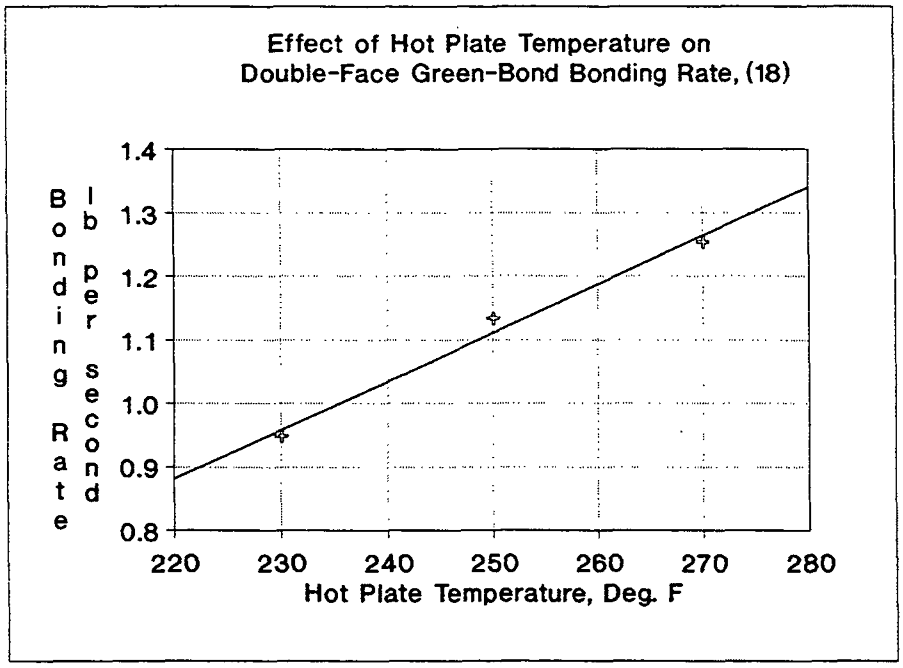


FIGURE 8.6
Effect of Hot Plate and Adhesive Temperature on Double-Face Green-Bond Bonding Rate



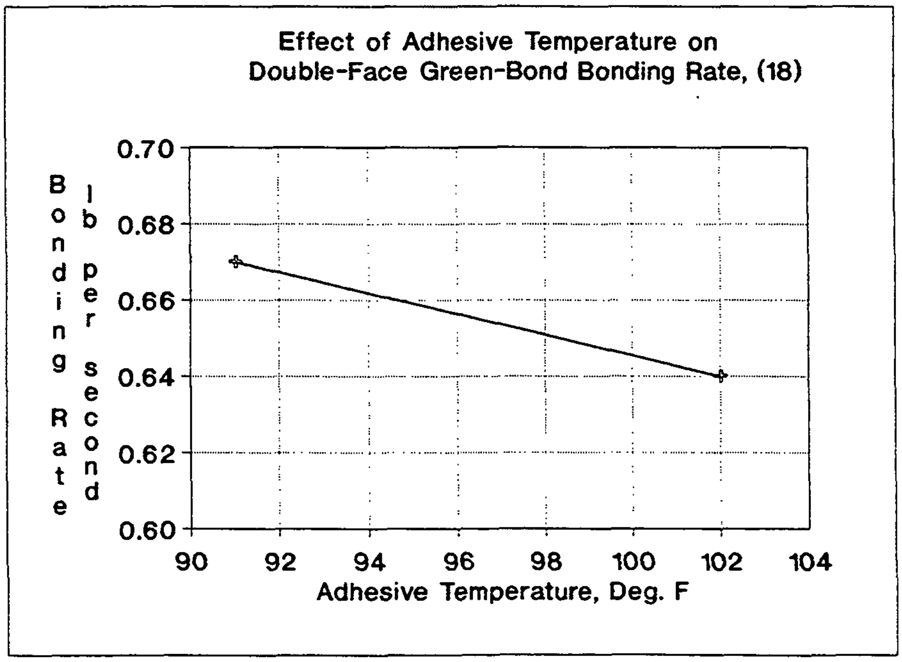


FIGURE 8.7
Effect of Adhesive Gel Point on Time to Achieve a Given Level of Double-Face Green-Bond Strength, (12)

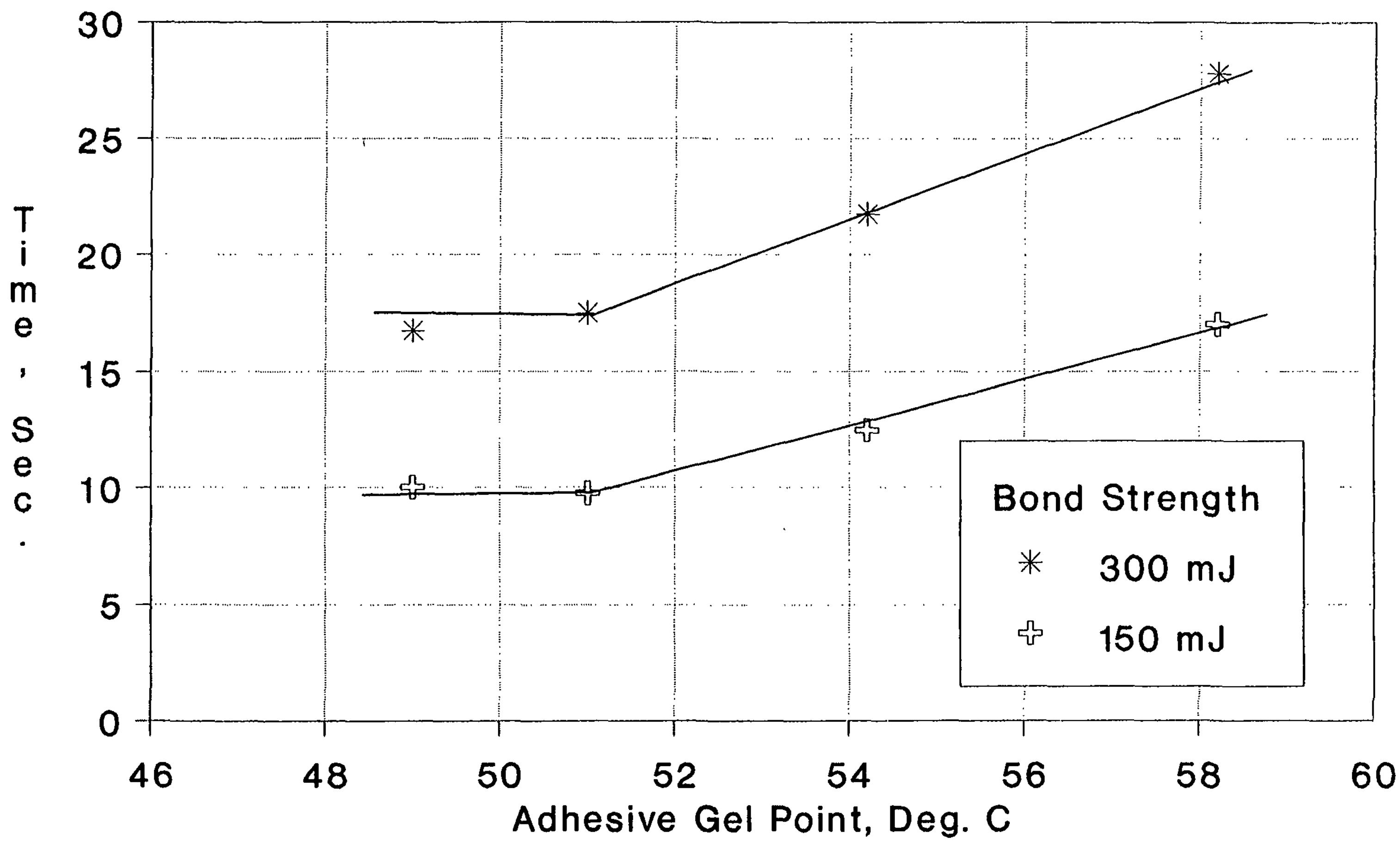
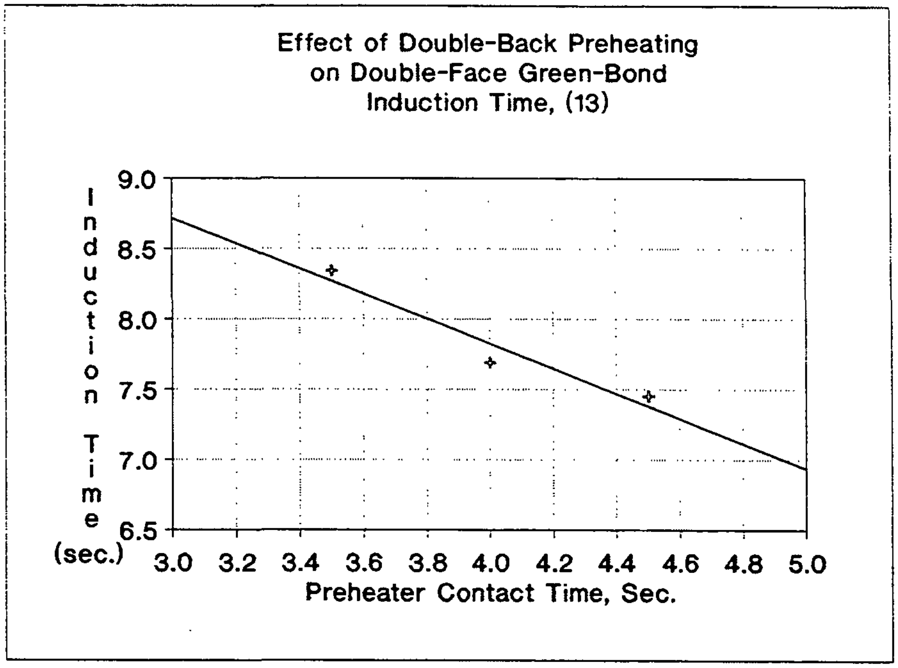
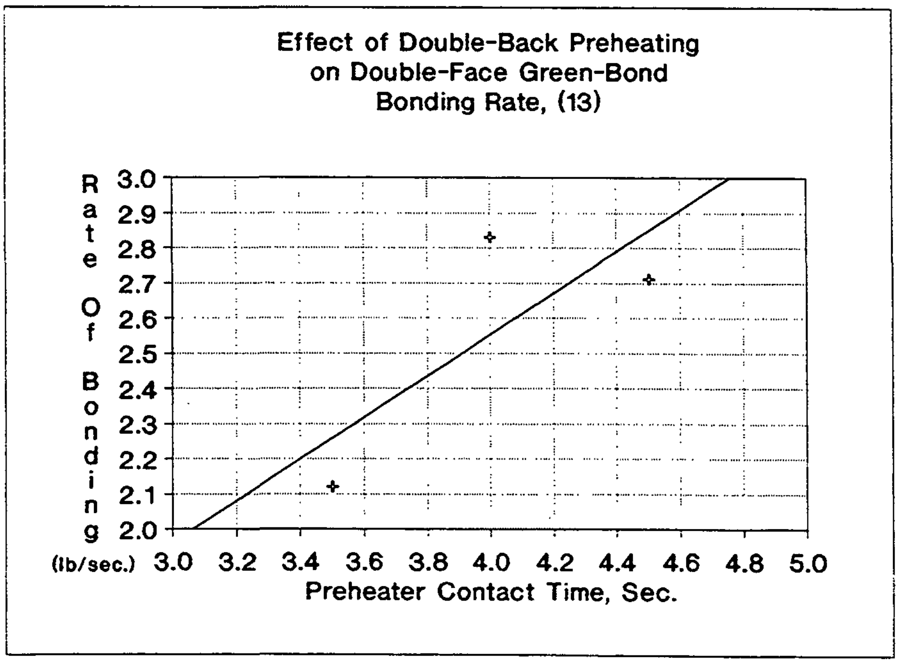


FIGURE 8.8
Effect of Double-Back Preheating on Double-Face Green-Bond Development





corrugating medium properties do not have a great effect on the double-face bond strength development, (12. 24, 71, 79, 83). However, the medium properties do have some influence as shown in ***Figure 8.9.***

The data used to develop the multiple regression equation were obtained with the double-backer simulator. The equation indicates that the double-face green-bond induction time is reduced by a medium with a lower flute tip water drop test, by a medium with a higher T-819 water penetration test, and by a less porous medium, (18). Both of the water receptivity tests are based on the time required for the medium material to absorb liquid. The equation indicates opposite effects for the two receptivity tests, and is, therefore, not clear as to the actual effect of this material property.

The technical information presented in this chapter on the development of the double-face bond strength supports the following observations.

1. The speed at which the double-face bond strength develops can affect the box plant waste and productivity costs. The strength of the green-bond determines the maximum permissible corrugator speed. The bond must not separate as it passes through the corrugator slitter/scorer unit and the cut-off knife.

2. The final, double-face bond strength is important to the compression strength and field performance of the corrugated box.

3. The double-face bond development curve exhibits an induction time, during which no measurable bond strength can be determined, and a rate of bond strength increase that is linear with bonding time, once the bond has started to form.

4. The medium material properties have little effect on the double-face bond strength development. There is one indication that a less porous medium may be beneficial.

5. Most of the double-face bond development characteristics are controlled by the process conditions which influence getting heat to the bond sites, and by the properties of the adhesive. An increased rate of double-face bond strength development can be achieved by:

   a. Increased preheating of the double-face linerboard and the single-faced webs.

   b. Higher hot plate temperature.

   c. Higher hot plate ballast roll or plenum pressure in the double-backer.

   d. Lower double-face linerboard basis weight.

   e. Lower double-face linerboard caliper, (increased density).

   f. Lower adhesive slurry gel point, (less heat needed to gel adhesive).

   g. Higher adhesive slurry solids content and viscosity, (less water).

   h. Lower adhesive application rate, (less water).

   i. Higher adhesive slurry temperature.

6. Slower corrugator speeds and longer double-backer hot plate and cooling sections do not affect the double-face bonding rate. They do, however, increase the bonding time available before the bonds are stressed at the corrugator slitter/scorer unit and cut-off knife.

FIGURE 8.9
Effect of Medium Properties on Double-Face Green-Bond Induction Time, (18)

$$IT = 9.94 + a(A) - b(B) - c(C)$$

$$r^2 = 0.792$$

IT = Green-Bond Induction Time, sec.

a = 0.0534
b = 0.0533
c = 0.107

A = Flute Tip Water Drop Test, sec.
B = T-819 Water Penetration, sec.
C = Gurley Porosity, sec.

Chapter 9

Combined Board Issues

There are many tests that can be performed on corrugated board samples. Some of the test results are influenced by the physical properties of the corrugated medium used to manufacture the combined board and some are not. The following is a partial listing of various combined board tests. The tests that are preceded by an asterisk are those that are influenced by the physical properties and attributes of the corrugating medium.

Combined Board Caliper
Flute Height
Linerboard Caliper
* Medium Caliper
* Combined Board Basis Weight
  Linerboard Basis Weight
* Medium Basis Weight
  Coefficient of Friction
  MD Edge Crush Test
* CD Edge Crush Test
  MD Flexural Stiffness
* CD Flexural Stiffness
* SF Pin Adhesion
* DF Pin Adhesion
  Slide Angle
* Flat Crush
* MD Torsion Tear
* CD Torsion Tear
  Scoreline Fold
* Water Resistant Bond
  Water Absorption Rate
  Mullen
* Klemm Test
  Hydrostatic Mullen
* Puncture
  Scuffing Test
  MD Scoreline Tensile
* CD Scoreline Tensile
  Scoreline Fold Cracking
* Tarnishing

The corrugating medium physical properties and attributes can affect the results obtained in 15 of the 30 tests listed. Those tests involved with basis weight and caliper do not require much technical discussion. Those tests involved with bonding are discussed in Chapters 6, 7, and 8.

The discussion of the remaining nine test parameters is limited by the amount of technical information available and found in the literature. The following three chapters cover the contribution of the corrugating medium properties and attributes to the characteristics of the combined board strength properties of Flexural Stiffness Test, Edge Crush Test, and Flat Crush Test.

It is important to keep in mind that the relationships between medium properties and combined board properties described in Chapters 10, 11, and 12 are, unless indicated otherwise, based on having good box plant fabrication quality. The results shown are not influenced by obvious fabrication defects such as high/low flutes, leaning flutes, fractured flutes, or poor corrugator bond strength. The effects of these process defects were discussed in previous chapters.

Chapter 10

Flexural Stiffness

The Flexural Stiffness Test is designed to measure the bending resistance of the corrugated board, Tappi T-820. The bending resistance of the corrugated board is directly related to the degree of side panel bulge that will occur in a box during stacking in a warehouse or due to a flowable product packed inside the box, such as resin pellets or the liquid held in a bag-in-box type of package. The combined effect of both the MD and CD flexural stiffness is important to box panel bulge resistance, (36, 99). The flexural stiffness strength is also one of the two corrugated board physical properties that determines the top-to-bottom compressive strength of a corrugated box, assuming adequate corrugator bond quality. The other corrugated board property is Edge Crush Test. A 10% change in the flexural stiffness strength of the combined board will result in a 2.5% change in box compression, based on the model developed and published by Mr. Robert McKee in 1963, (19, 24, 36, 73, 82, 99).

Corrugated board behaves the same as any other multi-ply structural material with respect to bending strength. The stiffness contribution of a given ply to the total stiffness of the structure is equal to the product of the elastic modulus of the material in the ply times the moment of inertia of the ply. The stiffness of the total structure is equal to the sum of the stiffness contributions of its parts. This assumes that there is no shear deformation between the plies in the structure. The moment of inertia of a given ply is related to approximately the cube of its distance from the bending center of the total, multi-ply structure. Since the linerboard plies are further away from the center of the corrugated board structure than the medium, they contribute more than the medium to the flexural stiffness of the board. In term of flexural stiffness, the medium serves primarily to keep the linerboard facings separated, (36, 99). In fact, the linerboard plies contribute between 90% and 95% of the total flexural stiffness of a typical singlewall corrugated board grade. This assumes, of course, that the medium does not have a major quality problem, such as fractured flutes. Since the distance of a ply from the center line of bending is so important to stiffness, flute height has a large effect. For a given grade of corrugated board, A-flute is much stiffer than C-flute, and C-flute is much stiffer than B-flute.

A schematic representation of the 4-point beam, Flexural Stiffness Test is shown in ***Figure 10.1.*** The 3-point beam Flexural Stiffness Test uses just one load point located midway between the two support points. The 3-point beam test is not used as a measurement tool for predicting box compression because of the fact that the shear properties of the medium are included as a factor in the measured stiffness value for the combined board.

Shear refers to the ability of the various plies in the sample to move with respect to each other. In the case of singlewall corrugated board, the plies in question are the two linerboard facings and the fluted medium. The easiest way to envision shear is to consider a stack of copier paper. The stack is rectangular in shape with the ends being square with the top and bottom surfaces of the stack. As the stack of paper is flexed, the individual paper plies slide against each other, as shown by the ends of the stack forming an angle to the bowed top and bottom surfaces. This is shear, and allowing shear to occur makes the stack of paper easier to bend. If all of the sheets in the stack were glued together, shear could not occur, and it would be much harder to bend the stack of paper.

The side panels of a box are bordered by the flap scores and the body scores. When the box is setup and the flaps are sealed, the four scorelines, defining a side panel of the box, in effect, clamp the edges of the two linerboard facing together and prevent shear from occurring. Shear does not occur in the 4-point beam test on corrugated board. This is why the 4-point beam test is the correct method to use for corrugated box applications.

The objective of the Flexural Stiffness Test is to measure the elastic region bending strength of the sample. The term elastic region simply means that the measured deflection remains linearly proportional to

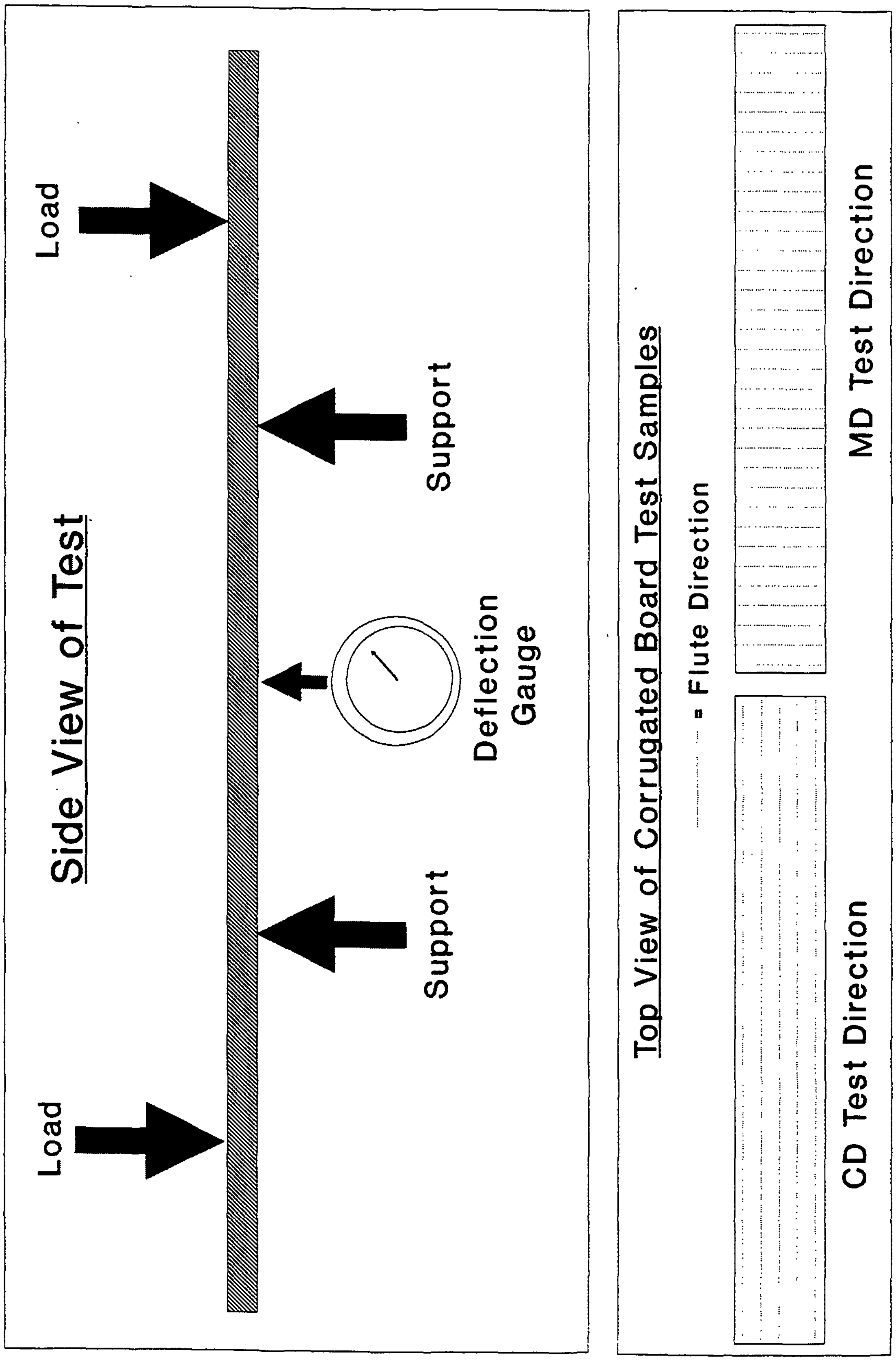


FIGURE 10.1
Flexural Stiffness Test

the load, that is, one unit more load produces one unit more deflection. It is necessary to achieve a sufficiently high deflection in the sample during testing to minimize the experimental error due to random variation. If, for example, the deflection gauge reading error was plus or minus 2 mils, a maximum deflection end point for a test specimen of 4 mils would have a 50% error probability. On the other hand, a deflection end point that is too high can produce values that exceed the elastic region for the sample and cause erroneously low flexural stiffness values.

Higher deflections also require higher test loading forces. Higher loading forces can result in crushing of the sample at the support points, and the crushing will lower the entire test specimen with respect to the deflection gauge. This will cause erroneously low deflection measurements and erroneously high measured flexural stiffness values.

The key to achieving valid flexural stiffness measurements is the use of the proper span distances between the two support points, between the two load points, and between the support and load points. Larger span distances produce larger sample deflections at lower applied load levels. The equation for calculating the flexural stiffness includes the span distances, so changing the span dimension does not affect the stiffness measurement. The span distances used should be based on the stiffness strength of the material. Stiffer materials should have greater span distances. The spans should be selected so that the load ranges used are about equal for all samples.

The cross direction (CD), flexural stiffness specimens have the flutes running parallel to the length of the sample. This CD orientation provides direct support from the fluted medium against crushing at the support and load points of the test instrument. The CD measurement direction also requires the fluted medium to bend as part of the total corrugated structure being flexed. The medium, then, does contribute the CD flexural stiffness. The machine direction (MD), flexural stiffness specimens have the flutes running perpendicular to the length of the sample. This MD orientation provides less support from the medium against crushing or deflection of the linerboard between flute tips at the support and load points of the test instrument. Also, the medium can deform in an accordion manner during the MD flexural stiffness testing, and, therefore, does not contribute directly to the measured MD stiffness strength. The medium only serves to maintain the spacing distance between the linerboard facings, (99).

Figure 10.2 shows the effect of medium basis weight on the flexural stiffness of C-flute board made with 26 lb/msf linerboard facings. ***Figure 10.3*** contains identical plots for the board made with 42 lb/msf linerboard facings, and ***Figure 10.4*** for the board made with 90 lb/msf linerboard facings. The data are summarized in ***Figure 10.5.*** All of the corrugated board was C-flute, combined on a commercial corrugator, and made with the same rolls of varying basis weight mediums. All of the data, except the MD, 90 lb/msf linerboard case, show little effect of increasing medium basis weight on the combined board flexural stiffness, (82). The MD flexural stiffness of the board made with 90 lb/msf linerboard was the highest level achieved in this study. The deviant data for this experimental condition may be explained by the span/load/crushing test instrument effect discussed above.

The legitimate assumption in 1976, when this study was conducted, was that a higher basis weight equalled a proportionately higher strength medium. Since 1991, Alternate Item 222/Rule 41 no longer requires a minimum medium or linerboard basis weight. The experimental results discussed in this chapter all use basis weight as the experimental design variable. "Basis weight" can be redefined as "medium strength," for the purpose of interpreting the significance of the data to today's corrugated board strength performance criteria.

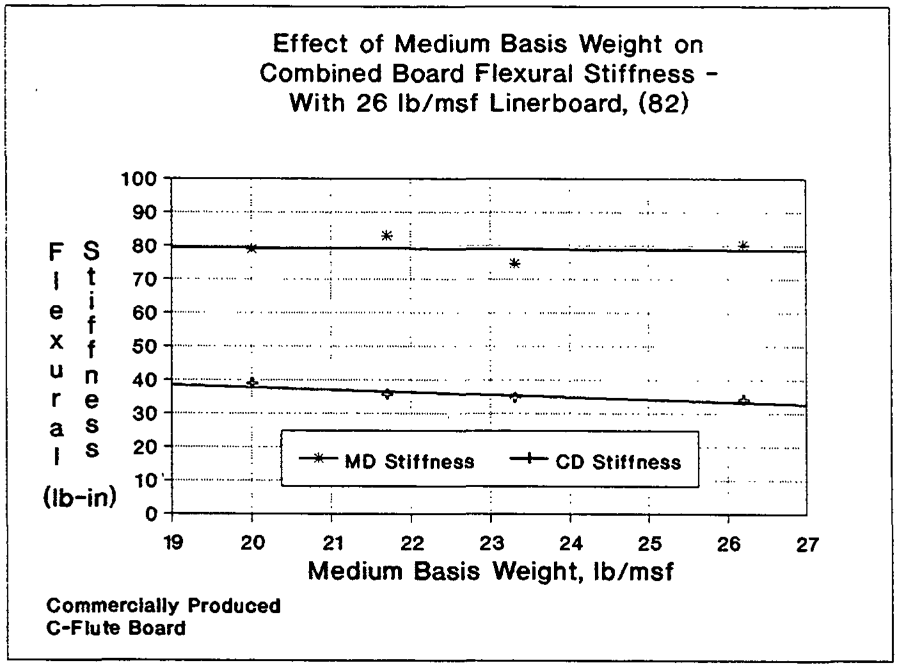
The relative contribution of the medium and linerboard to the combined board flexural stiffness is shown in ***Figure 10.6.*** The data show that increasing the linerboard basis weight (strength) has much more of an effect on improving the flexural stiffness of the corrugated board than an equal increase in the medium basis weight (strength). The slopes of the medium trend lines are much lower than the slope of the linerboard trend line, (82). This confirms the observations, discussed above, that the linerboard contributes more than 90% to the flexural stiffness strength of corrugated board.

Figure 10.7 shows the effect of linerboard basis weight on the flexural stiffness of C-flute corrugated board. The information shown is based on the results of a mathematical model, (19). The curvilinear relationship shown may reflect a reduction in the elastic modulus of linerboard with increasing basis weight or a span/load/crushing test procedure anomaly discussed above.

Figure 10.8 compares the flexural stiffness of two C-flute corrugated board materials made on a commercial corrugator using identical linerboard facings and two different basis weight grades of medium, 23 lb/msf and 37 lb/msf. The data show that a 61% increase in medium material (strength) increased the flexural stiffness by only 9%, (36).

Figure 10.9 shows the effect of flat crushing of the combined board flutes on the retention of flexural stiffness. The data show that the MD flexural stiffness is affected to a greater degree by crushing than is the CD flexural stiffness. An actual 50 mil crushing of the corrugated board produces a 39% loss in MD flexural

FIGURE 10.2
Effect of Medium Basis Weight on Combined Board Flexural Stiffness - 26 lb/msf Linerboard



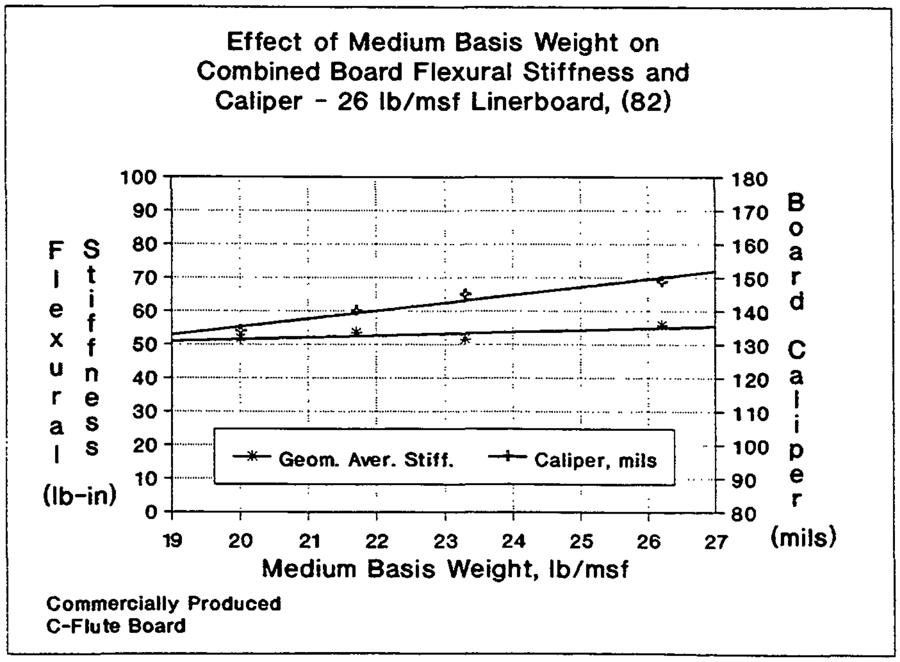
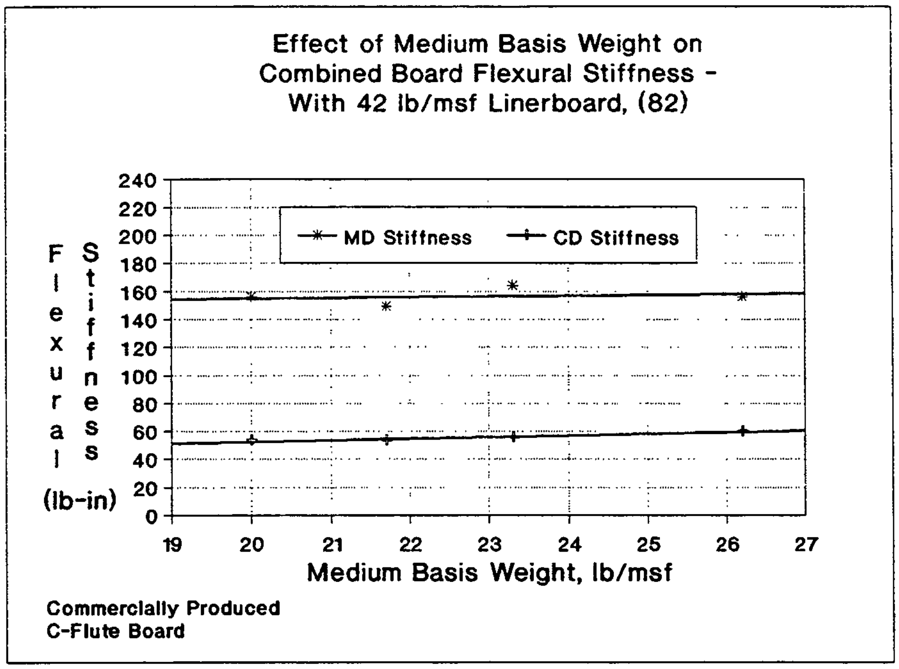


FIGURE 10.3

Effect of Medium Basis Weight on Combined Board Flexural Stiffness - 42 lb/msf Linerboard



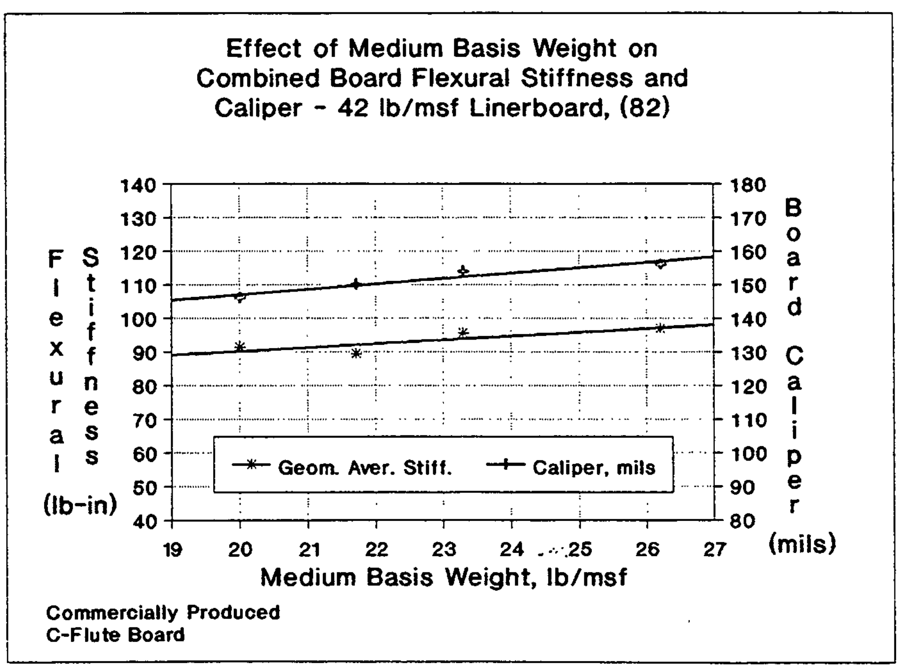
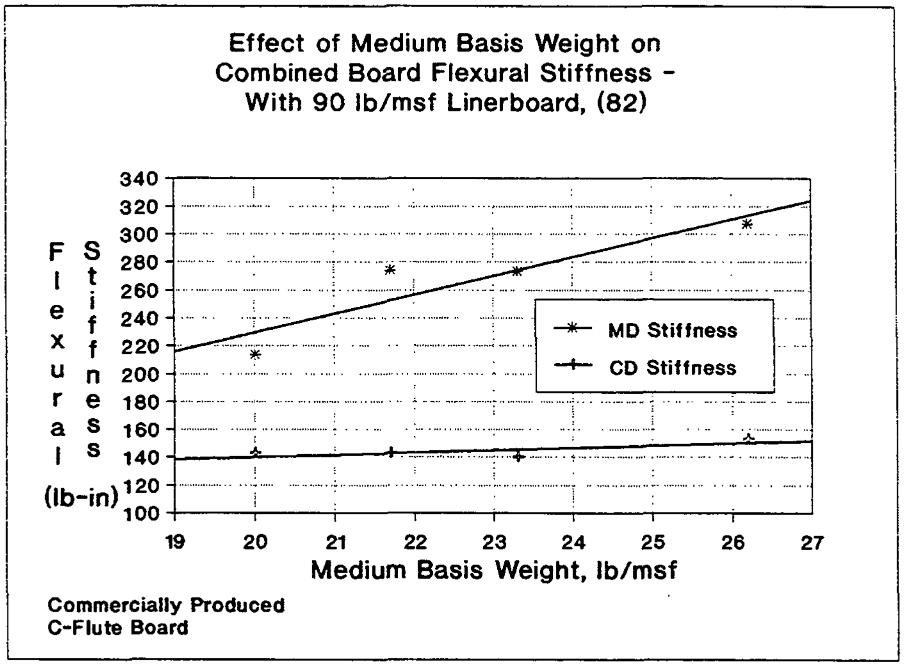


FIGURE 10.4
Effect of Medium Basis Weight on Combined Board Flexural Stiffness - 90 lb/msf Linerboard



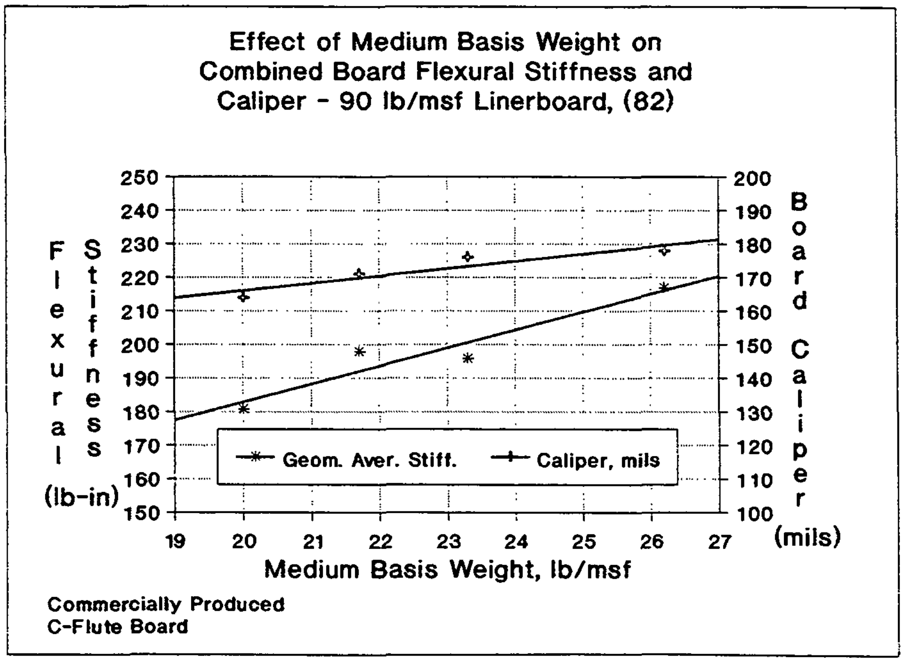
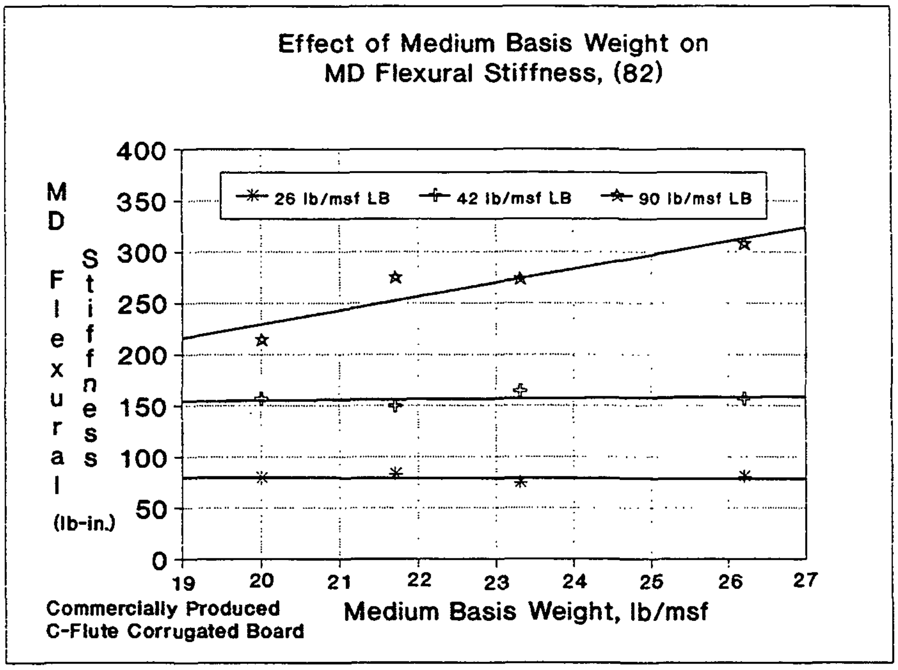
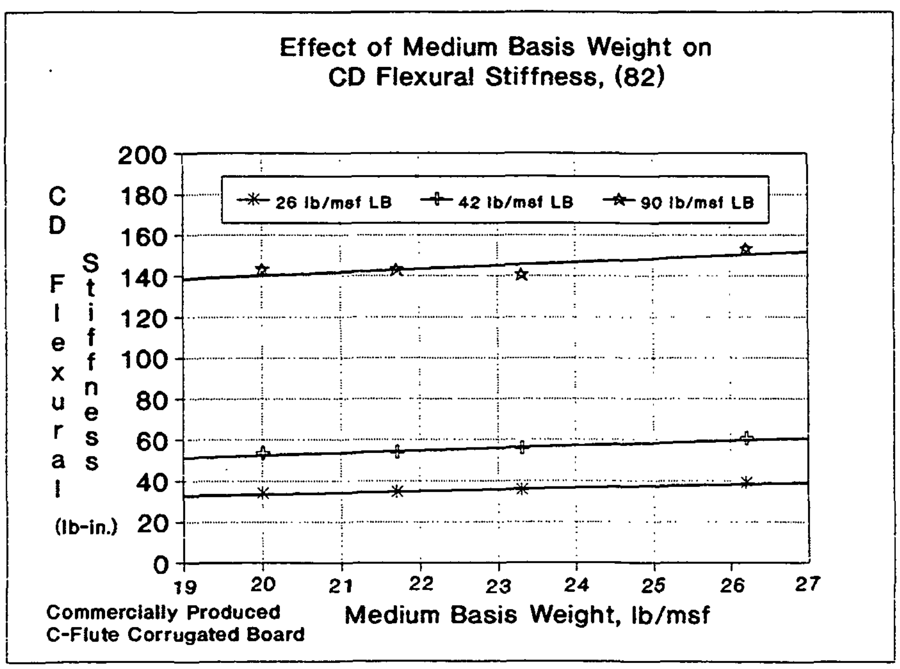


FIGURE 10.5
Effect of Medium Basis Weight on Combined Board Flexural Stiffness





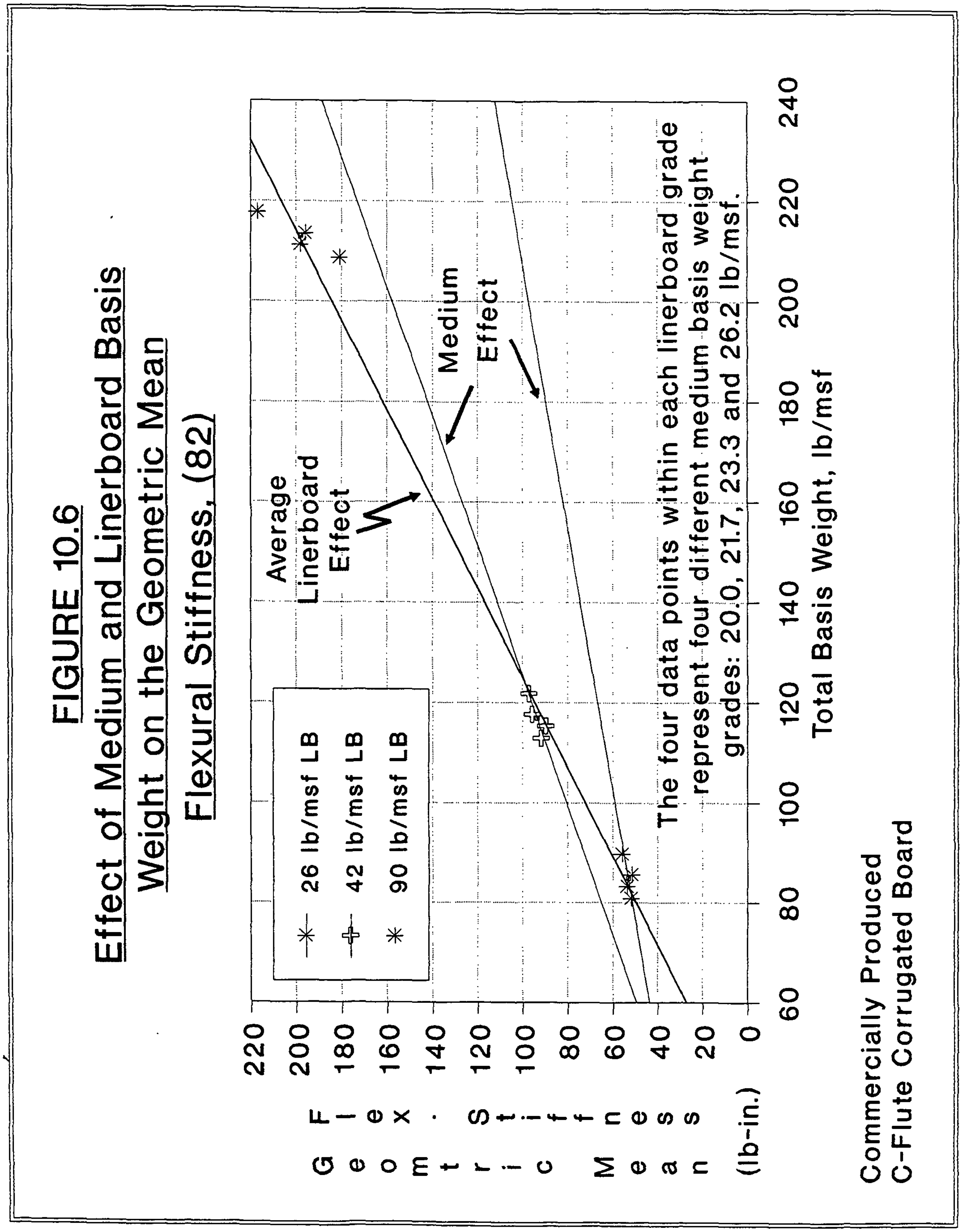
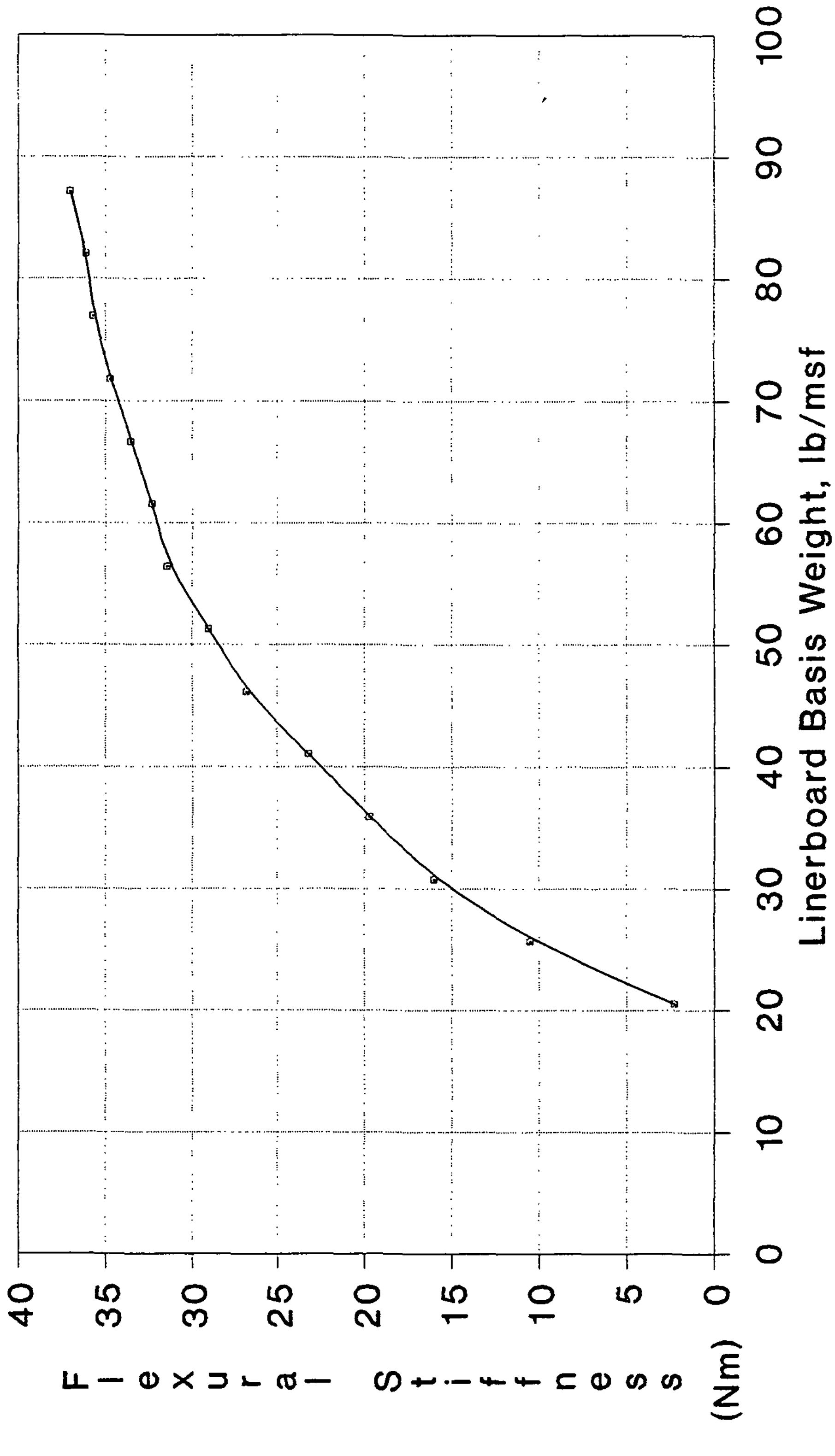


FIGURE 10.6
Effect of Medium and Linerboard Basis Weight on the Geometric Mean Flexural Stiffness, (82)

FIGURE 10.7

Effect of Linerboard Basis Weight on 4-Pt. Beam Flexural Stiffness, (19)



Data Points Not Shown.

FIGURE 10.8
Effect of Medium Basis Weight on Combined Board Flexural Stiffness

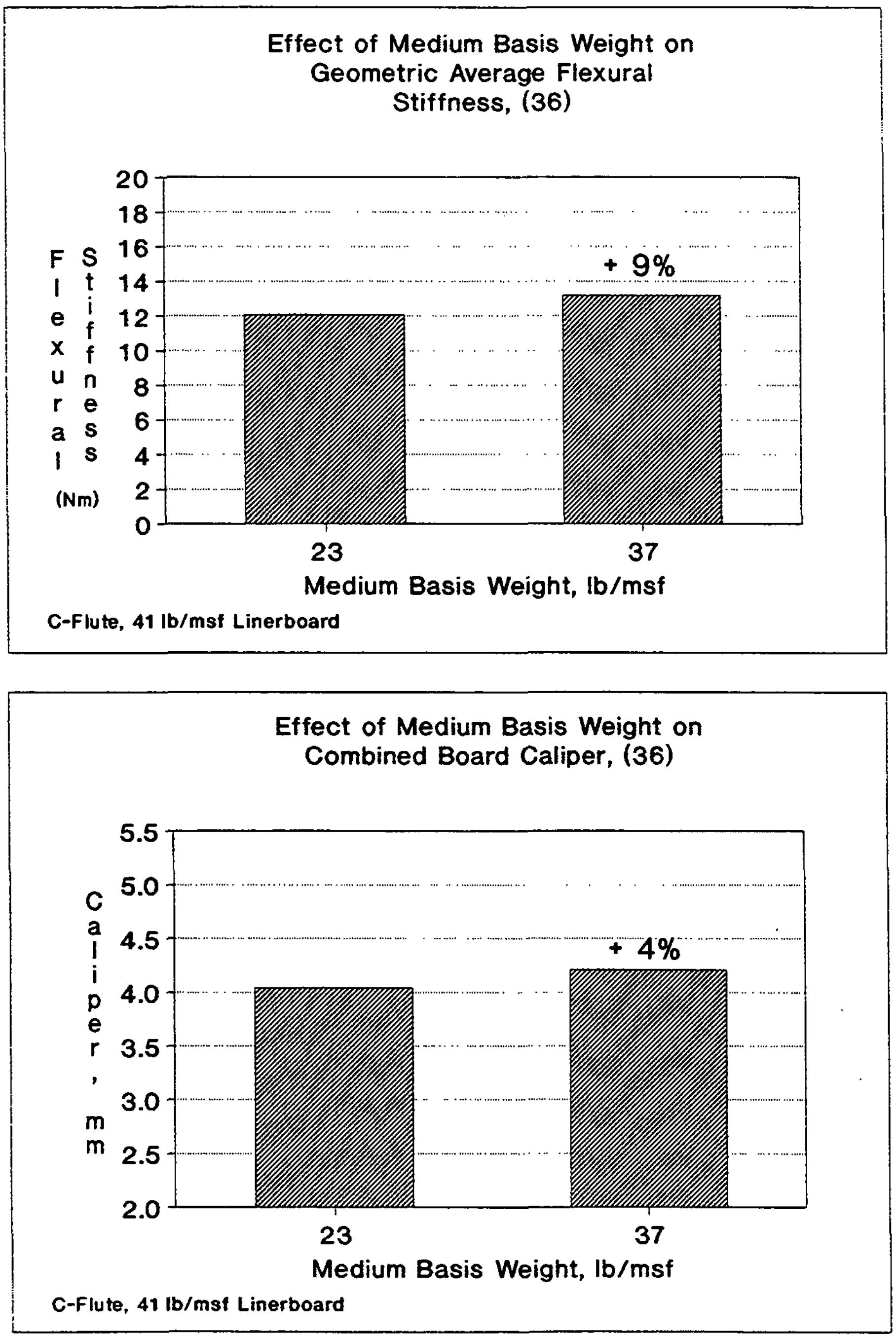
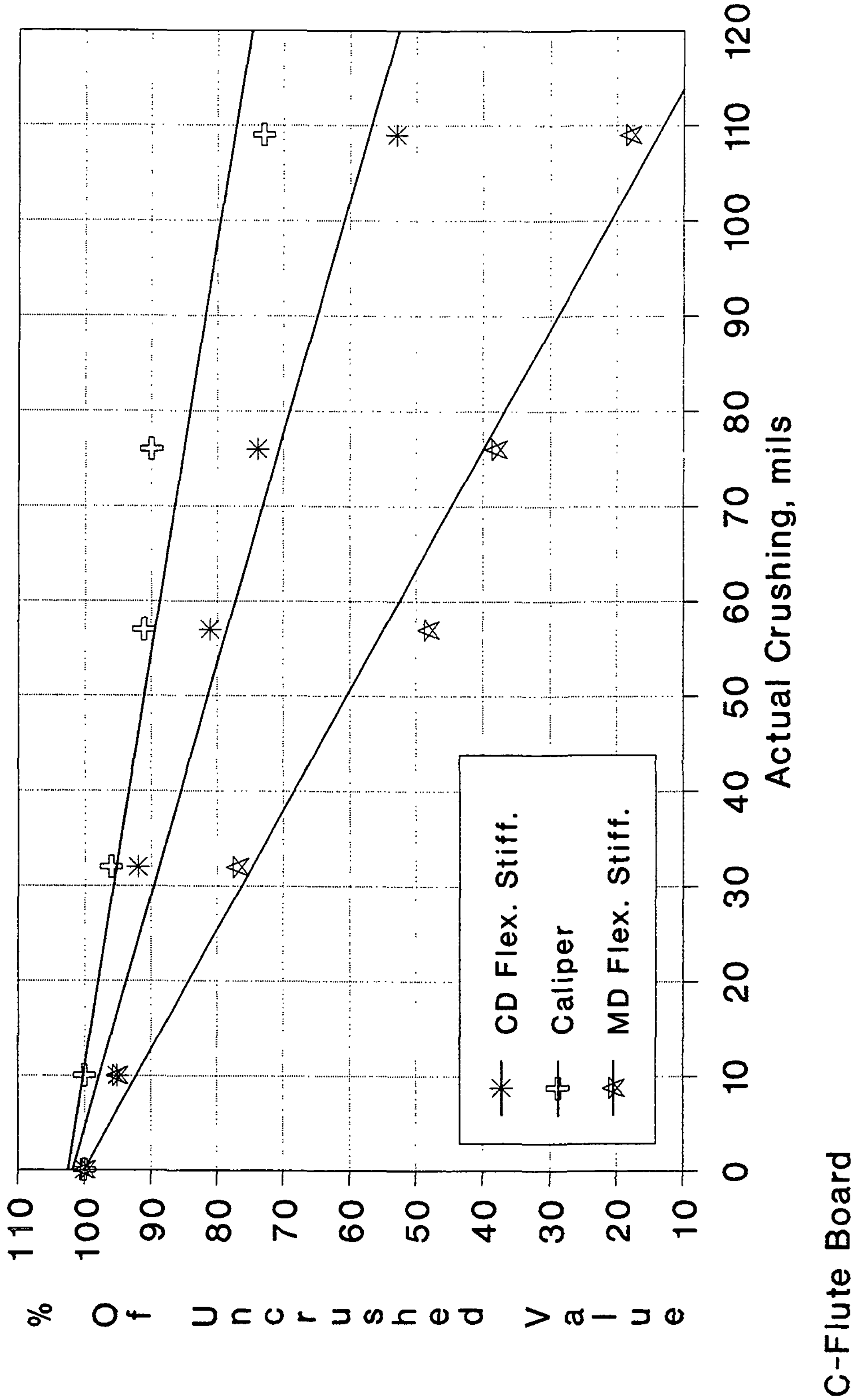


FIGURE 10.9
Effect of Combined Board Crushing on Combined Board Flexural Stiffness, (124)



stiffness and an 18% loss in CD flexural stiffness. The percentage loss in flexural stiffness in both directions is much greater than the measured caliper loss, (124). These data suggest that the empirical short form of the McKee box compression equation, which substitutes combined board caliper for combined board flexural stiffness, may be a much less sensitive model than the original McKee equation for recognizing the effect of box plant flute crushing quality defects on box compressive strength.

Figure 10.10 shows the effect of medium basis weight on the 3-point beam flexural stiffness. Based on this stiffness measurement method, a 61% increase in medium basis weight produces a 17% increase in the flexural stiffness, (99). This is approximately twice the effect shown in ***Figure 10.9*** for the 4-point beam test. The difference can be attributed to the added effect of medium basis weight (strength) on reducing the shear strain occurring during the 3-point beam test.

The data on flexural stiffness presented in this chapter support the following observations.

1. The 4-point beam test method should be used for corrugated board measurements of flexural stiffness since it eliminates the effect of shear in the medium on the measured strength. The 3-point beam test should not be used.

2. The span distances between the support points, between the load points, and between the support and load points should be adjusted based on the stiffness of the sample being tested. Greater distances should be used for stiffer samples so as to minimize the probability of crushing the corrugated board at the load and support points.

3. The flexural stiffness measurement should reflect the bending resistance of the sample in its elastic region.

4. The flexural stiffness strength of combined board is determined primarily by the linerboard facings and the height. Stronger linerboard and higher flutes improve the flexural stiffness of the corrugated board. This assumes no major corrugating defects in the medium, such as flute fracture.

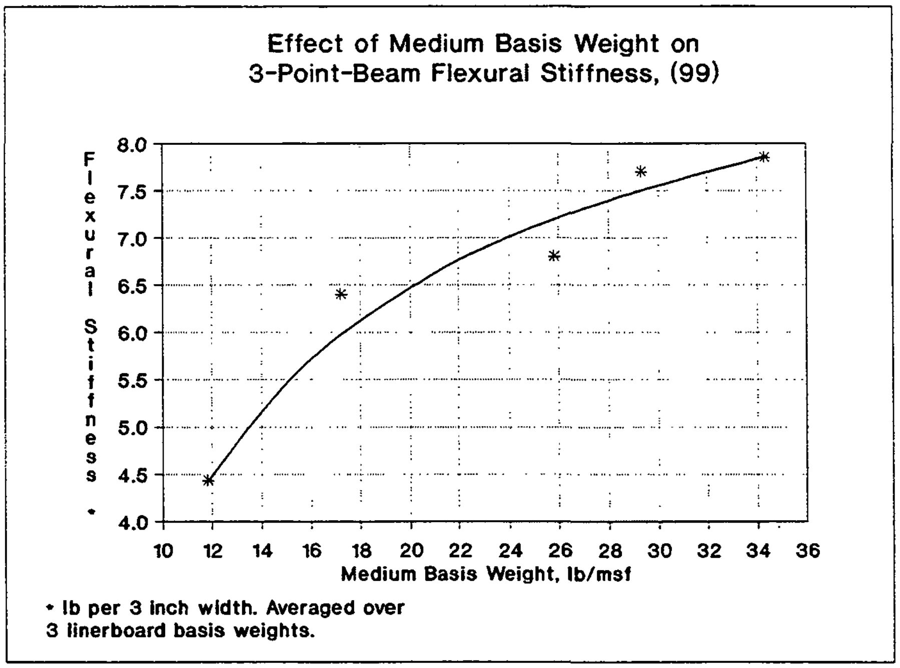
5. The main contribution of the corrugating medium to the combined board stiffness is to keep the linerboard facings separated and fixed.

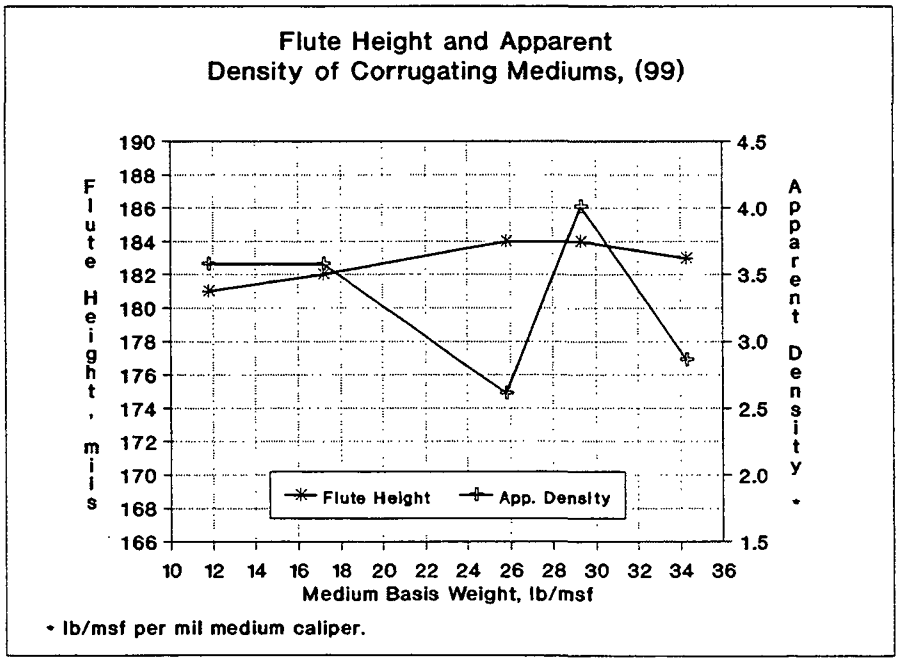
6. In singlewall board, a 61% increase in medium material only produces an approximate 9% increase in flexural stiffness.

7. Flexural stiffness is adversely affected by flat crushing of the combined board flutes. The MD flexural stiffness is more sensitive to crushing than the CD flexural stiffness. A measured 10% reduction in caliper caused by crushing results in an approximate 20% loss in CD flexural stiffness and a 48% loss in MD flexural stiffness.

8. This effect of crushing on the flexural stiffness strength demonstrates that the short form of the McKee box compression equation, which substitutes combined board caliper for combined board flexural stiffness, does <u>not</u> adequately reflect the loss in box compression due to the crushing of the medium flutes.

FIGURE 10.10
Effect of Medium Basis Weight on Combined Board Flexural Stiffness





Chapter 11

Edge Crush Test

The Edge Crush Test, ECT, of corrugated board is designed to measure the pure compressive strength of the material. The TAPPI Official Test Method T-811 specifies a test specimen height of 1.25 inch for B-flute, 1.50 inch for C-flute, and 2.00 inch for A-flute. The heights were selected to ensure that the test specimens will be stiff enough to resist bending or buckling during testing, and fail in pure compression. The only reason that the test procedure does not specify a 1.25 inch height for all of the flute sizes is a safety concern. The original procedure required the use of a circular saw to cut the test specimens. The objective of the test method was to allow as tall a test specimen as possible so as to keep fingers as far away from the saw blade as possible. Since C-flute is stiffer than B-flute, the C-flute specimen can be taller and still not bend or buckle during testing. The same is true for A-flute versus C-flute. The top and bottom edges of the test specimens are reinforced with wax to prevent test specimen edge failure, which is not representative of the true compressive strength of the material.

The ECT can be measured in both the cross direction, CD, and the machine direction, MD. The corrugating medium contributes directly to the compressive strength of the corrugated board in the CD test since the flutes are oriented vertically in the test specimen. The CD test is the most commonly run ECT test since most corrugated boxes have the flutes oriented vertically. The medium does not contribute directly to the ECT of the MD test. The compression load must be supported solely by the linerboard facings since the fluted medium can flex like a bellows. The medium does help to support the linerboard facings at the bonded area and does tie the linerboard facings together so they act as a unified structure. The bond sites, in effect, divide the linerboard into a series of short segments stacked on each other. This effect is controlled by the spacing of the flutes rather than by the strength of the medium itself.

The ECT strength is important because of its effect on the top-to-bottom compression strength of a corrugated box. The box compression strength calculation model, published by Mr. Robert McKee in 1963, shows that a 10% change in ECT strength causes a 7.5% change in box compressive strength, (36, 40, 116).

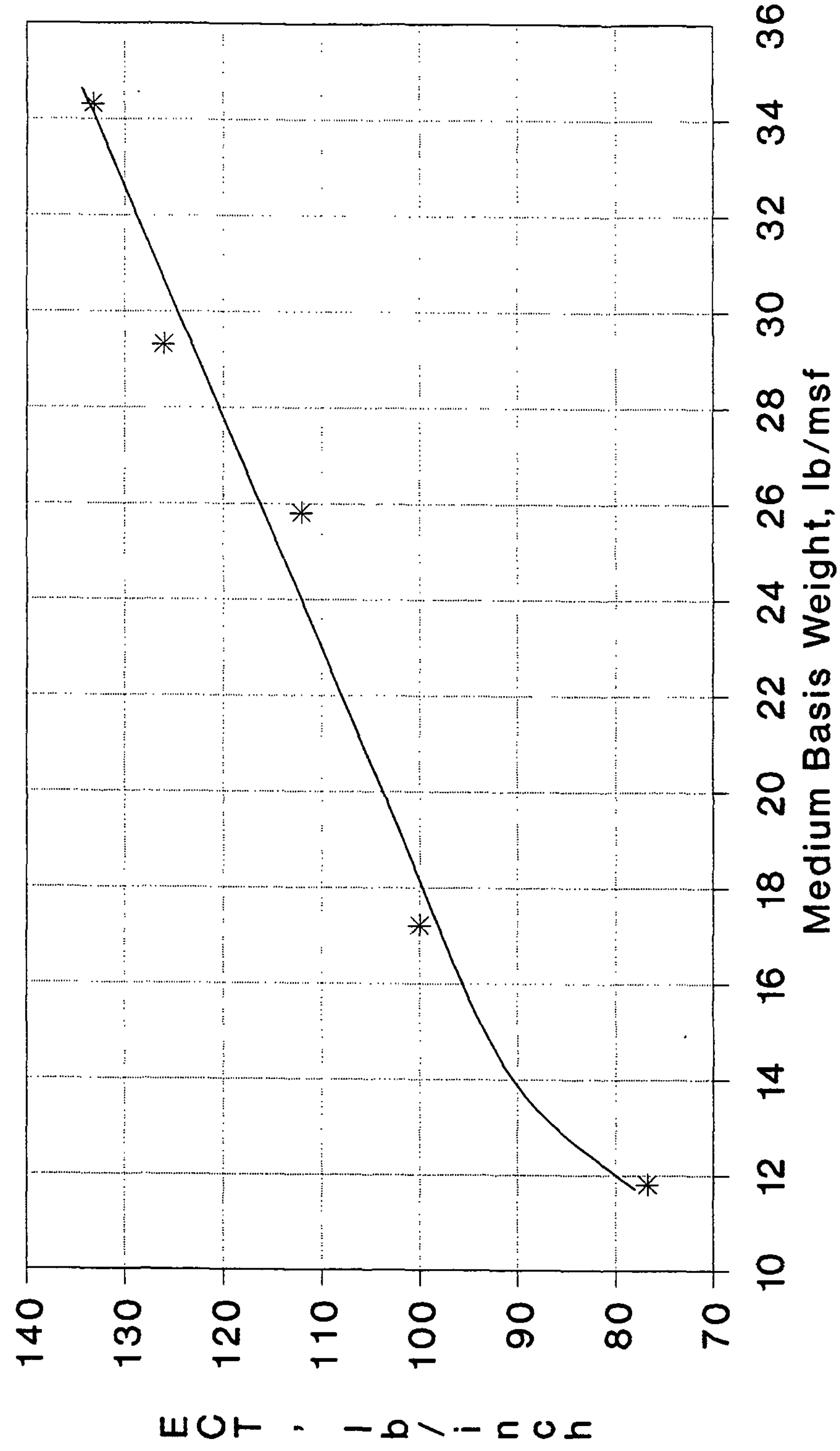
The CD ECT of corrugated board has been related to the sum of the compressive strengths of the linerboard and medium materials used in its construction. The contribution of the corrugating medium, of course, includes the effect of the flute draw factor, (16, 23, 39, 50, 54, 56, 82, 99,).

Figure 11.1 shows the effect of the medium basis weight on the combined board ECT. The effect shown is linear for medium basis weights above 19 lb/msf, and decreases more rapidly for medium with basis weights below 19 lb/msf, (99). At the time that this study was made, corrugating medium was considered a commodity item in which changes in basis weight were assumed to be directly proportional to changes in compressive strength, (54, 56, 64). This may or may not be true in today's technological environment.

It has been pointed out that the measured ECT can be less than the ECT calculated by the summation of the crush strength of the components. If the components reach their maximum strength at significantly different deflections, they will not reach their maximum strength at the same time in the ECT test. In this event, the measured ECT will be lower than predicted, (50). This concept of the effect on ECT of differences in the load deflection characteristics of linerboard and medium is similar to that of a box with an inner partition. A knowledgeable box designer specifies the height of the divider, which reaches a maximum compressive strength at about 0.1 inch deflection, so that it relates to the relative height of the taller box, which reaches its maximum compressive strength at about 0.5 inch deflection. If the two components of the package were made to the same height, the partition would fail in compression before the box reached its maximum load bearing capacity, and the package would not be as strong as it could have been if the proper relative heights were used.

Unfortunately, the height of the medium with respect to the height of the linerboard cannot be adjusted in corrugated board. They must be the same height. How-

FIGURE 11.1
Effect of Medium Basis Weight on
Combined Board Edge Crush Test, (99)



Averaged over three
linerboard basis weights.

ever, the characteristics of the compression stress/strain curves of materials can be used as a design tool to properly match materials.

The two most common ways currently used to measure the compressive strength of linerboard and corrugating medium is the Ring Crush Test, TAPPI T-822, and the Short-span (STFI) Test, TAPPI T-826. One published relationship between the two test methods for corrugating medium is shown in ***Figure 11.2***. The data show a reasonable linear relationship, (39).

The author wishes to state that, in his opinion, an absolute and universal correlation between the two tests will never be possible. A good empirical correlation can be obtained for a given set of samples, but the correlation can change if the fibers are changed or if the bonding between the fibers is changed by a paper machine process change. The two tests are measuring two different aspects of the compression strength of paper. Virtually all physical properties of paper can be related to the strength of the individual fibers in the paper, and to the amount of bonding between the fibers and the strength of those bonds. Typical hardwood fibers are about 0.9 mm long, and typical pine fibers are about 3 mm long. The STFI Test uses a span of 0.7 mm. The Ring Crush Test uses a specimen height of 12.7 mm. The STFI Test emphasizes the individual fiber strength over bonding strength, relative to the Ring Crush Test, and vice versa. Which is better? The author will not state his opinion!

The relationship between medium basis weight and the combined board ECT is shown in ***Figure 11.2***. The linerboard was held constant, and the combined board was manufactured on a pilot-size corrugator. Forty-nine different samples of commercial corrugating medium, ranging in basis weight from 26 lb/msf to 52 lb/msf, were used in the study. The relationship is shown to be linear, with a correlation coefficient of 0.974. ***Figure 11.3*** shows the relationship between the medium CD ring crush strength and the combined board CD ECT, and between the medium CD STFI crush strength and the combined board CD ECT. Both show linear relationships. The correlation coefficient, for this set of data, was slightly higher for the Ring Crush Test than for the STFI Crush Test, being 0.995 and 0.977, respectively. Other studies by the same researchers have shown that the STFI Test was a better indicator of ECT than the Ring Crush Test for extremely densified medium products. This later study used Formette handsheets and a pilot-size corrugator for the experiments, (29, 39).

Figure 11.4 shows the relationship between the corrugating medium CD ring crush strength and the combined board CD ECT for both C-flute and B-flute board. The experiments were conducted using commercial medium materials and a commercial corrugator. The data show a directly proportional increase in ECT with increasing medium ring crush strength. The C-flute and B-flute grades responded equally, that is, the slopes of the two regression lines are the same, (82). The difference in off-set between the lines is greater than can be explained by just the difference in draw factor between the flute sizes. The greater than expected difference may be explained by differences in the corrugating quality (bond strength, crushing, flute lean, fracture, etc.) that might be expected in a commercial process.

Figure 11.5 demonstrates the effect of the medium flute fracture defect on the ECT of the combined board. The experiments were run on a pilot size corrugator using commercial medium. The degree of fracture represented by the data was not severe. It was just at the start of fracture, close to the breakpoint between good and defective corrugated board. This low degree of fracture reduced the ECT by almost 15%, (129).

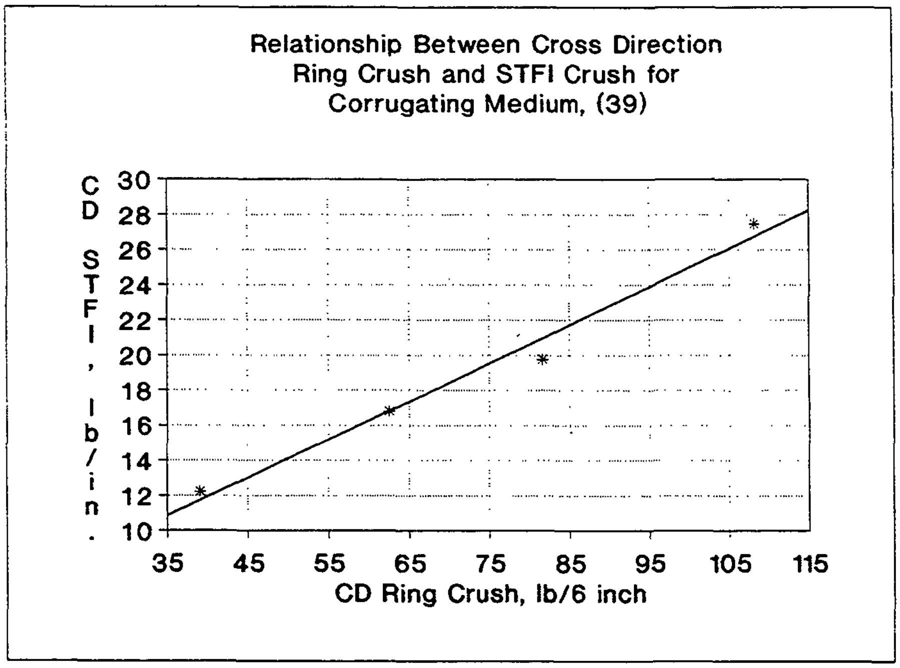
The effect of corrugator adhesive gaps, like the old fingerline gap, is shown in ***Figure 11.6***. The experiments were conducted on a pilot-size corrugator using commercial medium. The various size gaps were induced by using a scrapper blade on the glue applicator roll in the single-facer. The relationship shows a slightly curved shape. A 0.1 inch gap reduces the combined board ECT by 4%, a 0.4 inch gap by 17%, and a 1.0 inch gap by 32%, (116). The 0.5 and 1.0 inch glue gaps very seldom occur in real life. However, blisters do occur in this size range, and a blister is equivalent to a glue gap since the bond between the medium and the linerboard is not formed even though the adhesive is present. The effect shown in ***Figure 11.6***, therefore, applies to blisters, fluff-out, and loose edge defects as well.

Figure 11.7 presents a regression equation which relates the corrugated board quality defects of leaning flutes, single-face pin adhesion bond strength, high/low flutes, actual crushing, and pressure roll cutting to the combined board ECT. The experiments were done on a pilot-size corrugator using commercial medium and linerboard. A full factorial experimental design was used so that any interactive effects could be determined. No such interactions were shown by the data. The variables were found to be additive. For example, the loss in ECT due to crushing will be directly added to the loss in ECT due to leaning flutes, even though both defects reduce the caliper of the combined board, (5). An interactive effect means that two variables act together in a way that makes their combined effect greater or less than the sum of their individual effects.

All five defects had a statistically significant effect on ECT. All had an adverse effect, except for the pressure roll cutting which had a positive effect. It is hypothesized that the favorable effect of the pressure roll cutting is due to a slight decoupling of the linerboard and medium at the bond sites, which allows the linerboard and the medium to reach their maximum strength at closer to the same ECT deflection, as was discussed in

FIGURE 11.2

Relationship Between CD Ring Crush and CD STFI & Between Medium Basis Weight and Edge Crush Test



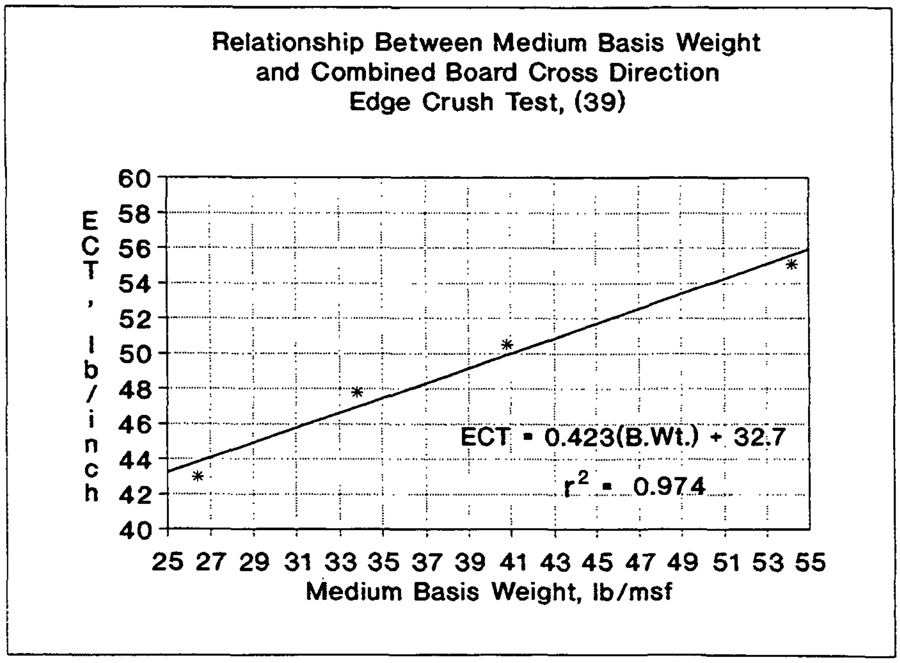
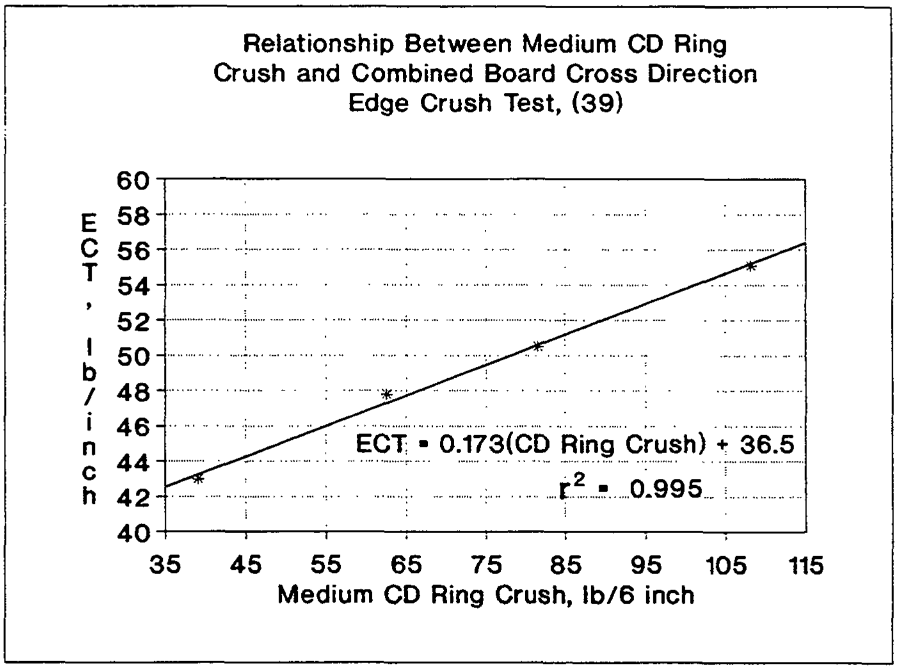


FIGURE 11.3

Relationship Between CD Ring Crush and CD Edge Crush Test & Between CD STFI and CD Edge Crush Test



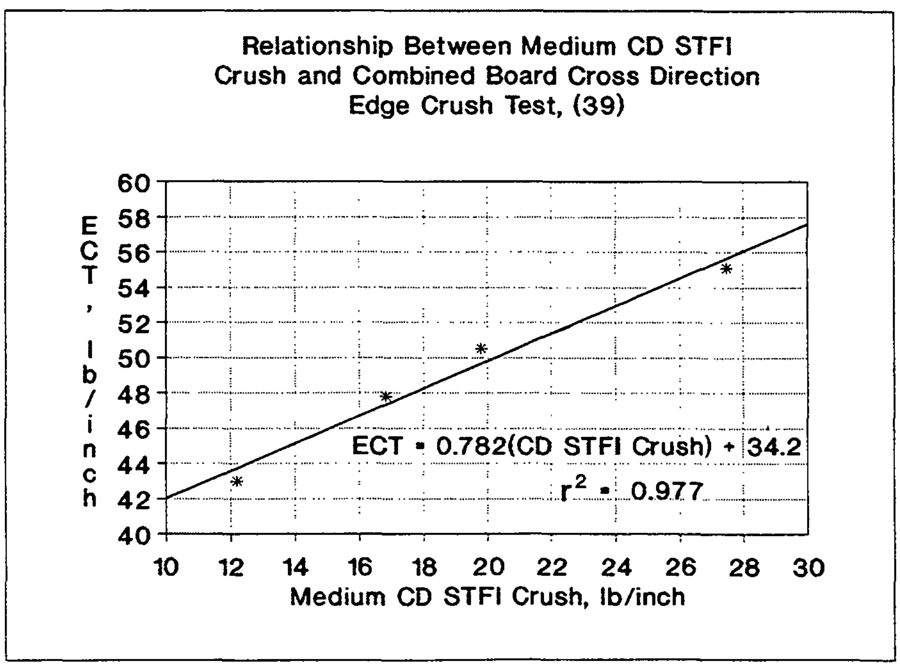


FIGURE 11.4
Relationship Between Medium Ring Crush and Combined Board Edge Crush Test, (82)

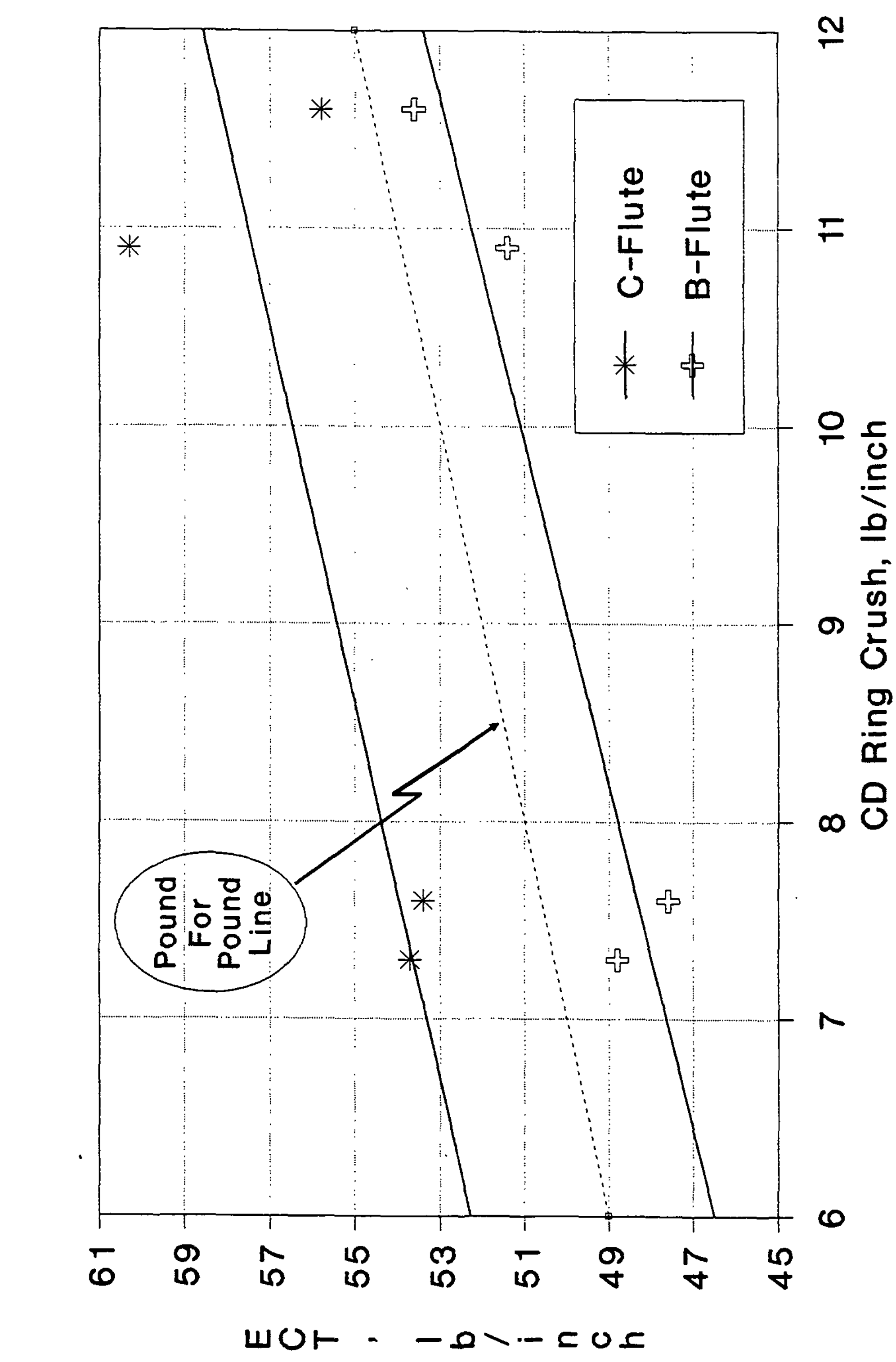


FIGURE 11.5

Effect of Flute Fracture Defect on Fluted Medium Edge Crush Strength. (129)

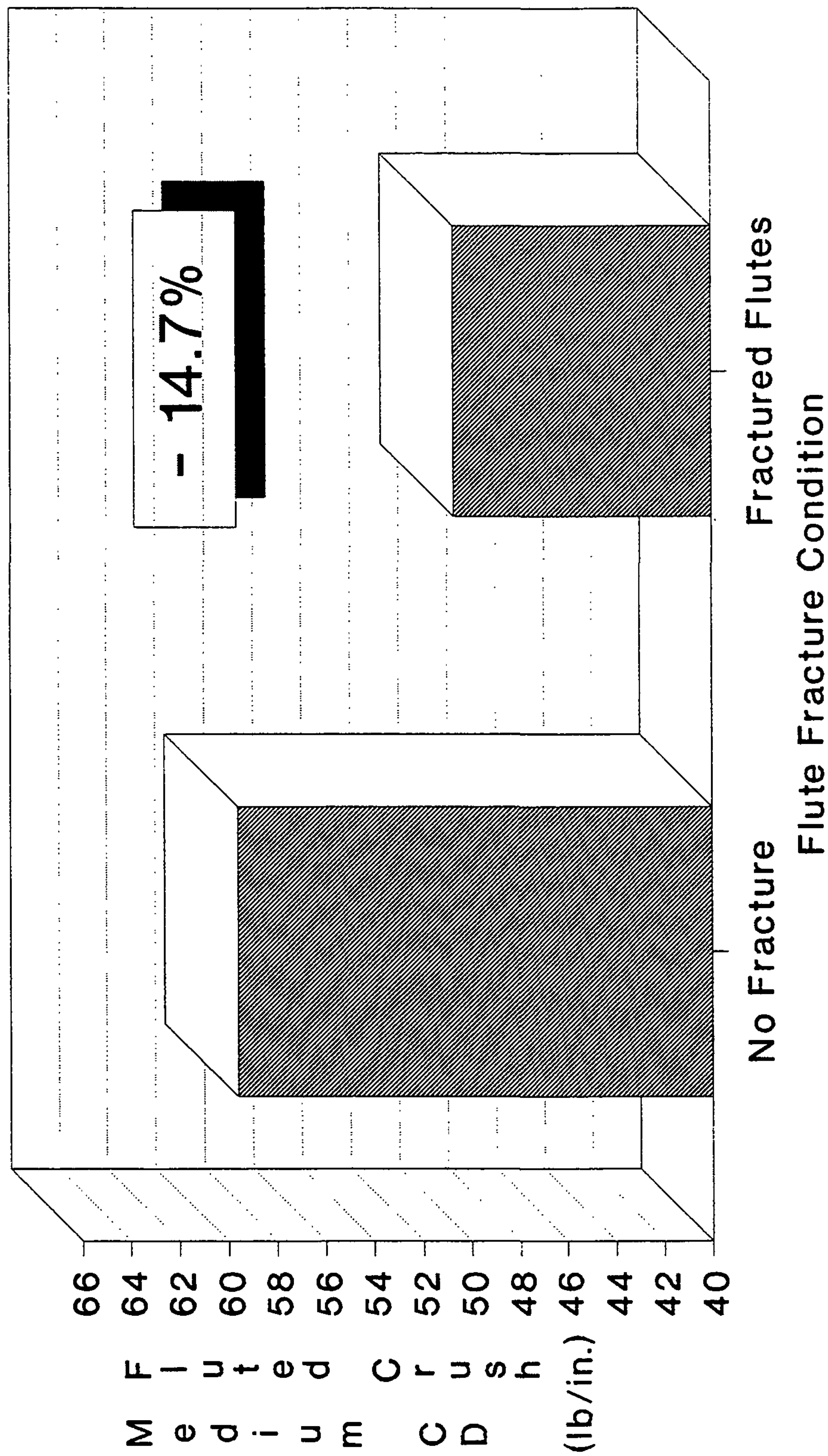


FIGURE 11.6

Effect of Adhesive Gaps on Combined Board CD Edge Crush Test. (116)

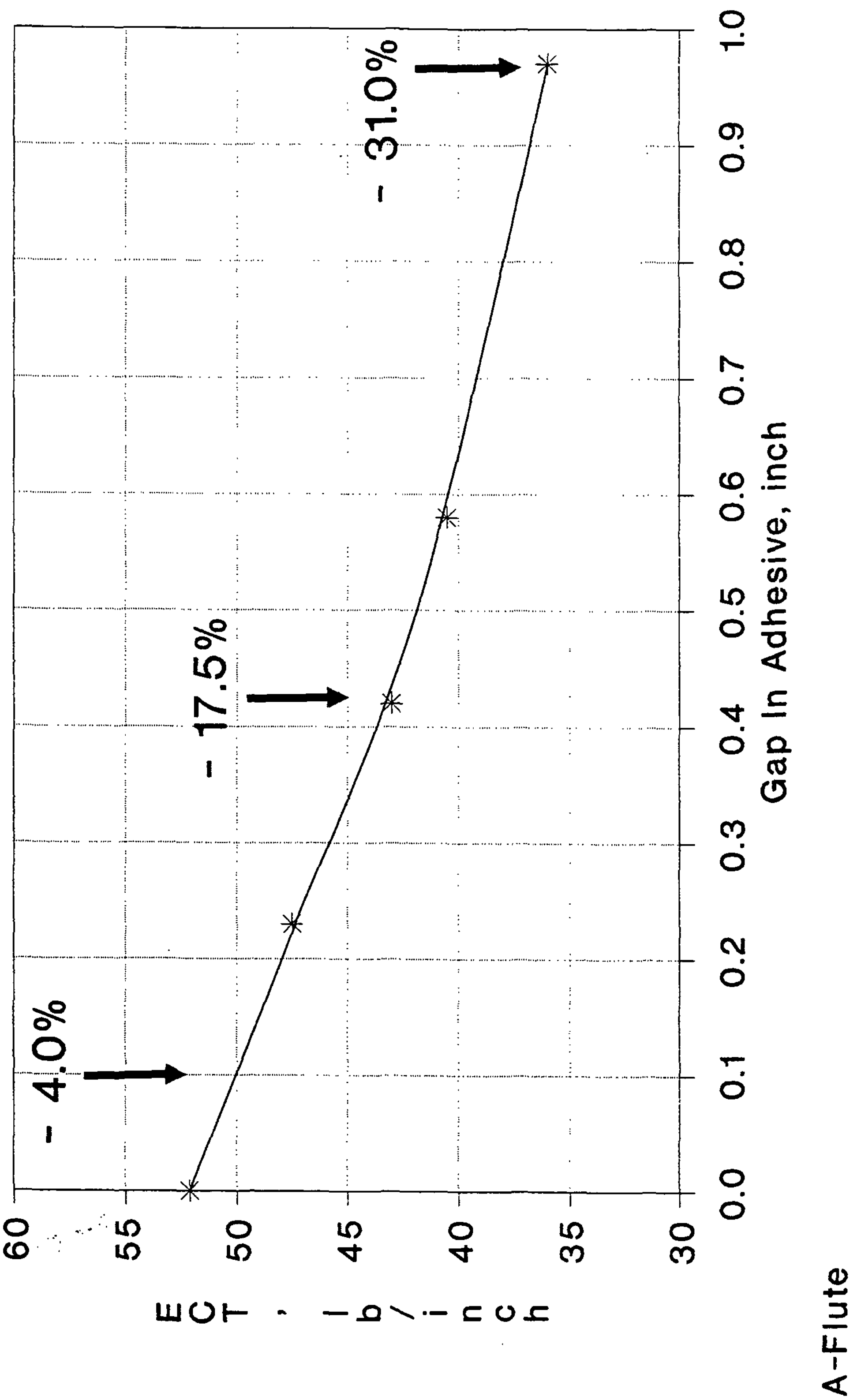


FIGURE 11.7
Effect of Box Plant Process Variables on Combined Board CD Edge Crush Test, (5)

$$ECT = 33.7 - a(A) + b(B) - c(C) - d(D) - e(E)$$

$r^2 = 0.750$ $n = 216$

ECT = Edge Crush Test, lb/inch

a = 0.0397	A = Leaning Flute Angle, Deg.
b = 0.150	B = Single-Face Pin Adhesion, lb
c = 0.0534	C = High/Low Flutes @ 4 mils Or Greater, %
d = 0.134	D = Actual Crushing, mils
e = 0.130	E = Pressure Roll Cutting, % Mullen Loss

the sixth paragraph of this chapter. The researcher does not recommend that a box plant use pressure roll cutting to increase ECT because of other package quality issues, such as scoreline splitting, mullen strength, and puncture resistance, (5).

The regression equation shown in ***Figure 11.7*** indicates a 1.5 lb/inch reduction in ECT for every 10 lb decrease in single-face pin adhesion. While the study did not include the double-face bond strength, there is no reason to believe that the effect would be any different than that shown for the single-face bond. Having a good quality and a strong corrugator bond is an inexpensive way to add to compressive strength. Conversely, an attempt to save on adhesive costs by excessively decreasing the adhesive application rate and thereby reducing the strength of the corrugator bond is a very costly way to experience box failure, (5, 7).

Another researcher reported an initial increase in ECT with crushing before it leveled off and then decreased, ***Figure 11.8***. No hypothesis was offered by the researcher to explain this experimental observation, (7, 124). The author has no explanation to offer and is of the opinion that some experimental error or data transposition error may have occurred.

Box plant personnel frequently use combined board caliper measurements to judge the degree of crushing taking place in the box plant process. ***Figure 11.9*** shows the relationship between the actual crushing and the measured crushing of 42-26-42 lb/msf C-flute corrugated board. The crushing was done in a laboratory using a rubber-to-steel roll nip, and with the flutes of the combined board being oriented perpendicular to the nip axis during the crushing. The actual crush is represented by the measured gap clearance at the crushing nip. The data show that the measured crush is considerably less than the actual crush. On average, the difference is a ratio of approximately 1:7. It also shows that caliper measurements on corrugated board are very variable, even under controlled laboratory conditions and using the average value of 10 measurements on each small size sample.

Figure 11.10 shows the actual crushing versus measured crushing for A-flute corrugated board. It also shows the influence of medium basis weight on the difference between the actual and the measured crushing. The difference between actual and measured crush for A-flute is approximately the same magnitude as was shown for C-flute board in ***Figure 11.9***. The heavier basis weight medium (stiffer medium) shows a greater caliper recovery than the lower basis weight medium, (130). ***Figure 11.11*** shows the difference between a steel-to-steel roll nip and a rubber-to-steel roll nip. The steel-to-steel nip shows an average 6 mil greater measured crush than the rubber-to-steel roll nip, at equal measured nip clearances. The difference can be attributed to the "give" or compressibility of the rubber roll, (130). This compressibility effect is the principle of the so-called "no-crush" feedrolls that are being sold commercially. ***Figure 11.12*** shows the effect of repeated crushing of the same sample of corrugated board. Above an actual crushing level of 20 mils, repeated crushing results in larger, permanent, measured caliper loses, (130).

The speed of the caliper recovery in corrugated board after crushing is shown in ***Figure 11.13*** for both a 15% and a 28% actual crushing level. The material used in the study was C-flute board made with 26 lb/msf medium. The data show that more than 90% of the caliper recovery occurs within 1 minute after crushing. This recovery rate is much quicker than the time it takes a machine operator in a box plant to cut and measure a sample of board for crushing, (5).

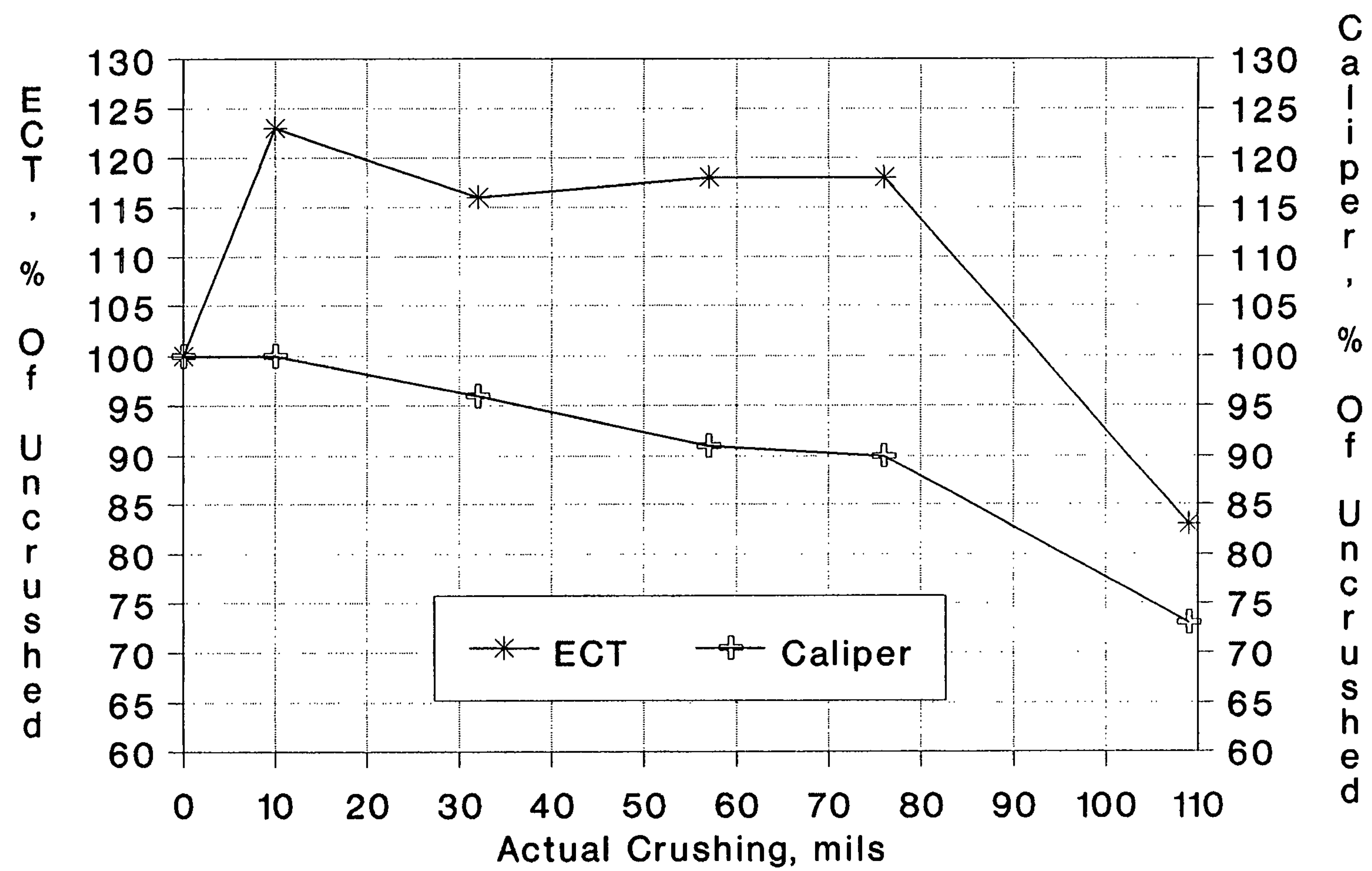
The data indicate that actual crushing of 25 mils or less in a commercial box plant manufacturing operation is not statistically detectable at the 95% probability level, even under the best of circumstances, by the use of combined board caliper measurements. An actual crush of 25 mils will produce a 3.4 lb/inch reduction in ECT, or 7.8% of the most common singlewall grade. This estimate is based on the regression equation shown in ***Figure 11.7***. An alternative approach for a box plant operation to consider for controlling the crushing defect may be to measure and control the actual gap clearances at the various nip points in the corrugated board and boxmaking processes.

A regression equation relating corrugating process variables and corrugating medium properties to ECT is presented in ***Figure 11.14***. The data were generated using a pilot-size corrugator and commercially produced corrugating mediums. The equation shows that the ECT decreases with decreasing medium basis weight, decreasing medium STFI crush strength, increasing corrugator speed, decreasing corrugator bond strength, and increasing severity of high/low flutes, (16). The quantitative effect of the high/low flute defect on ECT in this study is approximately equal to the magnitude of the effect described in the regression equation shown in ***Figure 11.7***. The two equations show a greater difference in the predicted effect of the corrugator bond strength, (5, 16).

Figure 11.15 shows the effect of corrugating medium properties on the retention of CD crush strength in the medium after fluting. The experimental data were generated on a pilot-size corrugator using both commercial mediums and Formette handsheet mediums. The fiber furnishes included NSSC, Green Liquor, Caustic Carbonate, and Recycled. The equation predicts that a medium with higher MD, CD, and ZD (thickness) elastic modulus properties will retain more of its CD compressive strength after fluting, (1, 39).

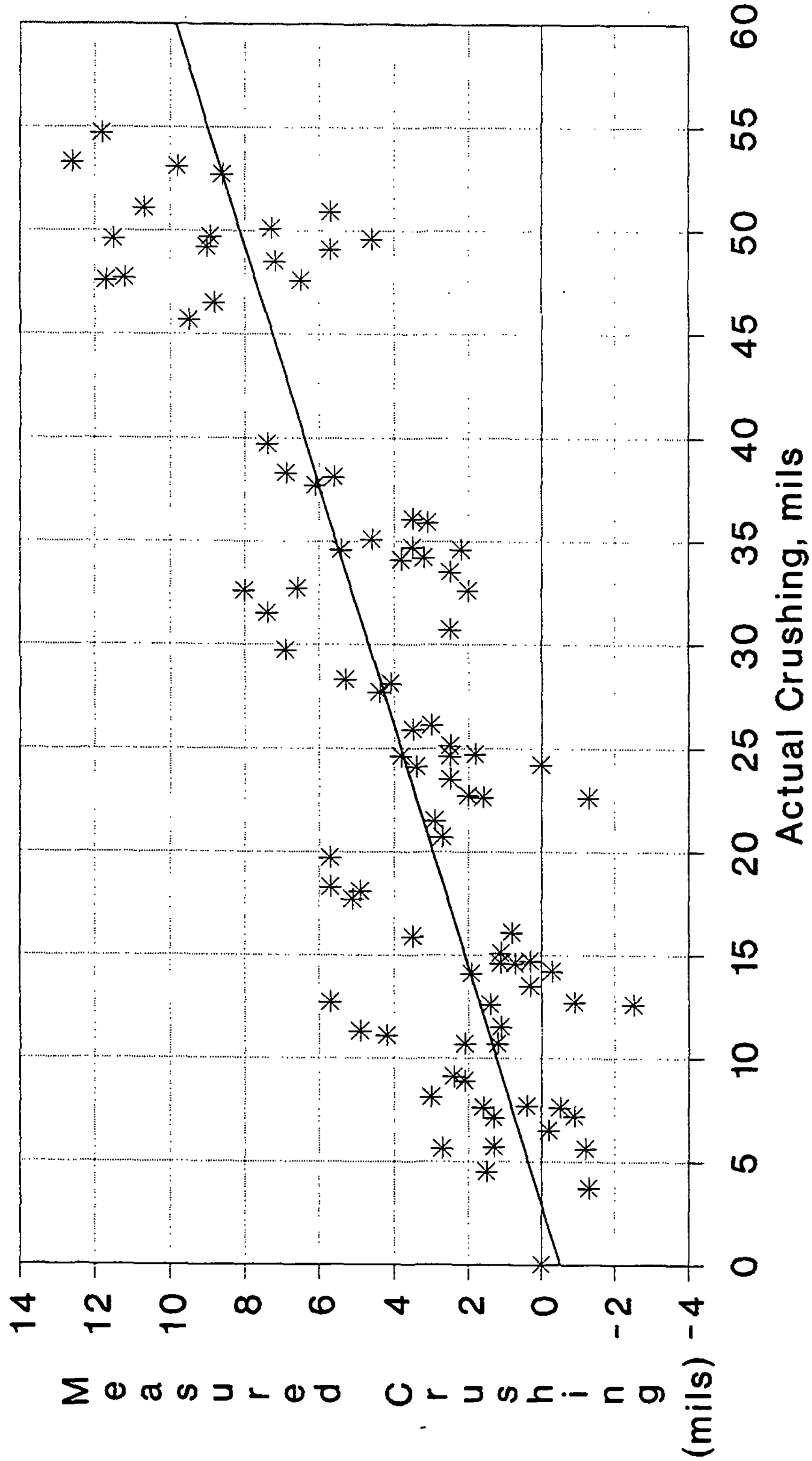
Figure 11.16 shows the impact of paper mill pulp refining and paper machine wet pressing on the retention of the corrugating medium CD crush strength after flut-

FIGURE 11.8
Effect of Combined Board Crushing on CD Edge Crush Test, (124)



C-Flute Board

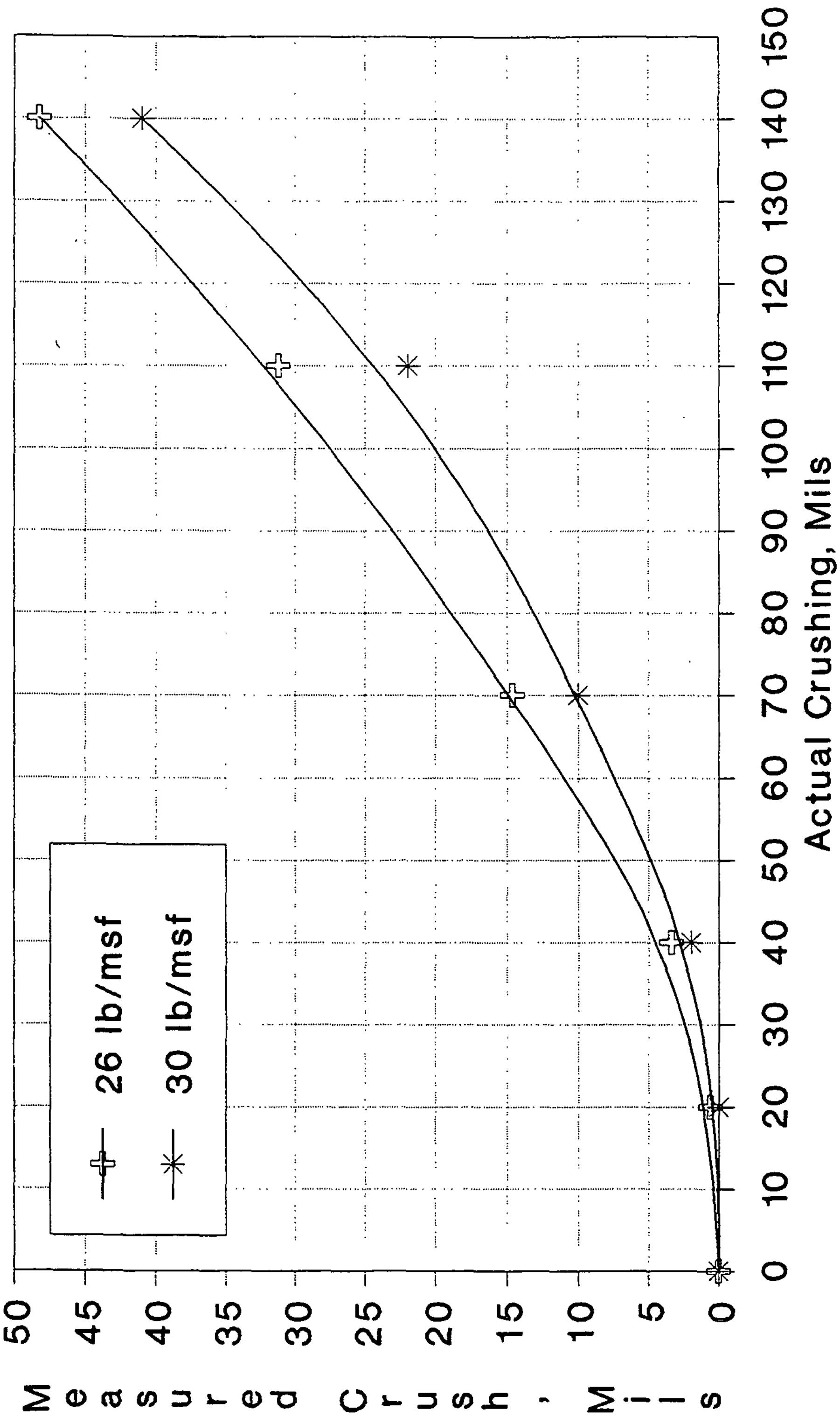
FIGURE 11.9
Relationship Between Actual Combined Board Crush and Measured Crushing, (5)



42-26-42, C-Flute Construction.
Rubber/Steel Roll Crushing Nip.

FIGURE 11.10

Effect of Medium Basis Weight on Measured Caliper After Crushing. (130)



A-Flute Corrugated Board.

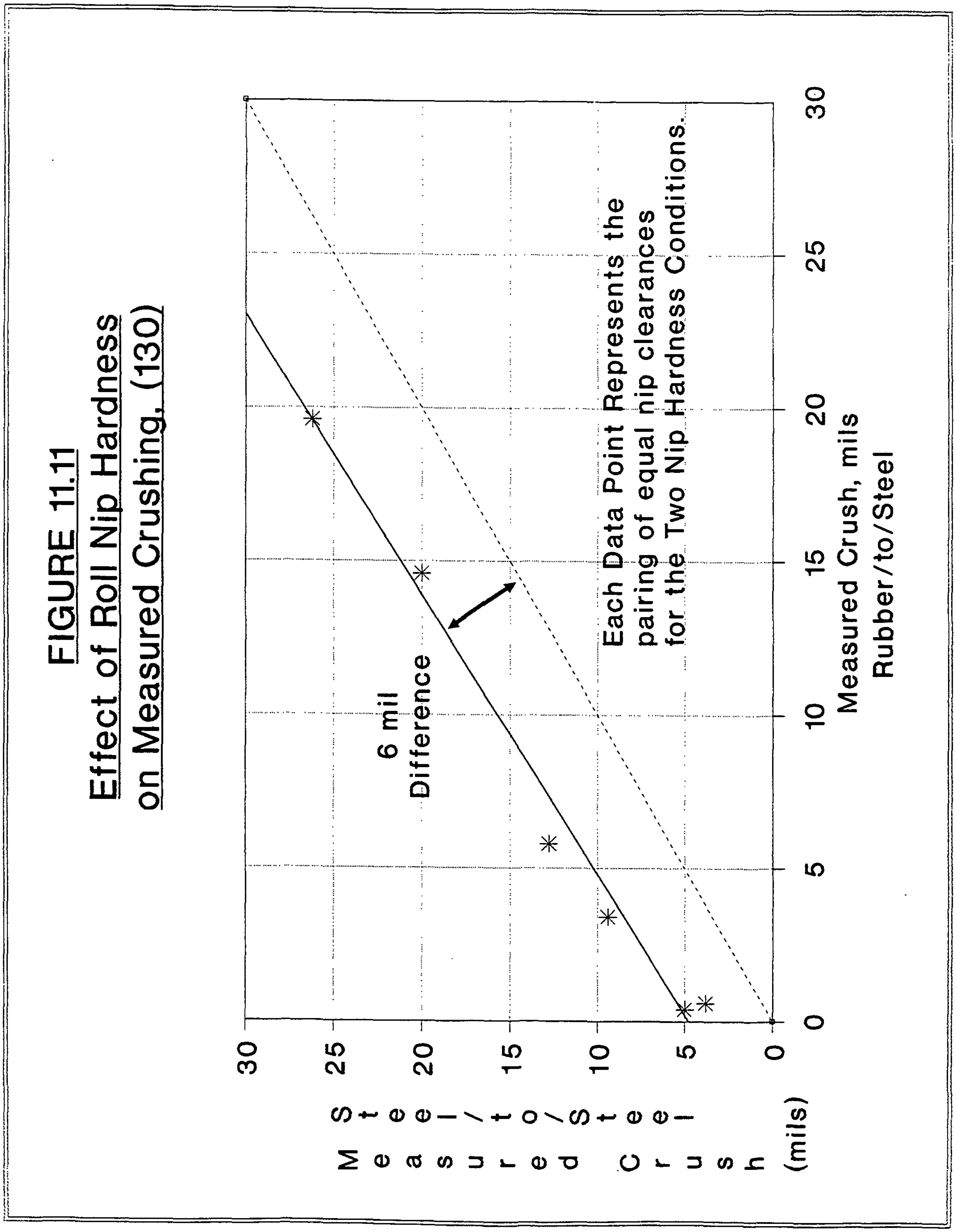
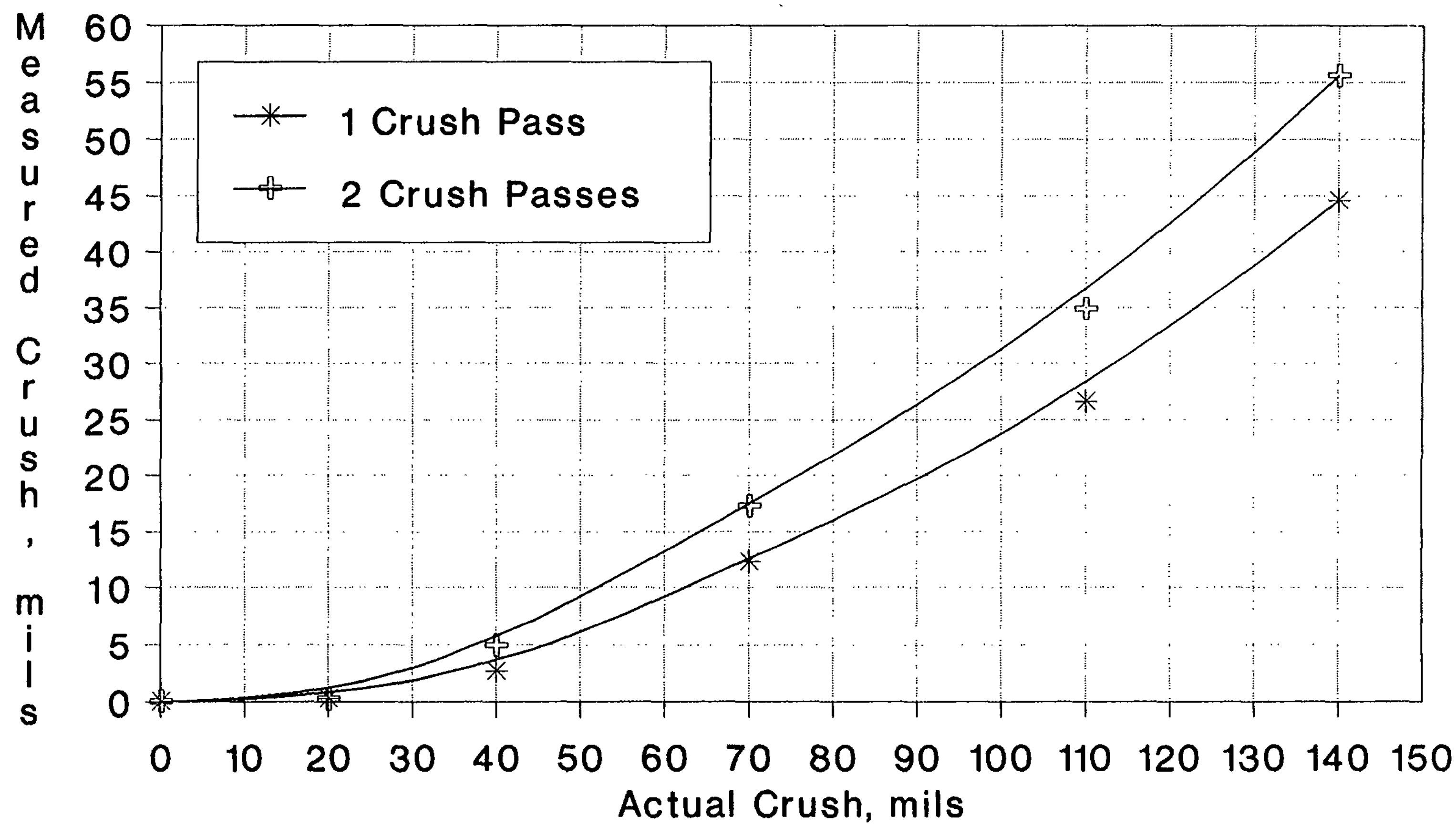


FIGURE 11.11
Effect of Roll Nip Hardness
on Measured Crushing. (130)

FIGURE 11.12
Effect of Multiple Crushing
on the Measured Crushing, (130)

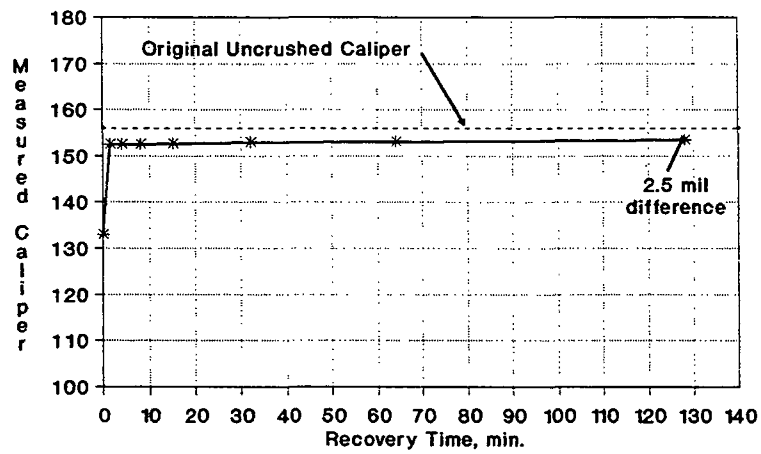


Average for A-Flute,
26 & 30 lb/msf Medium.

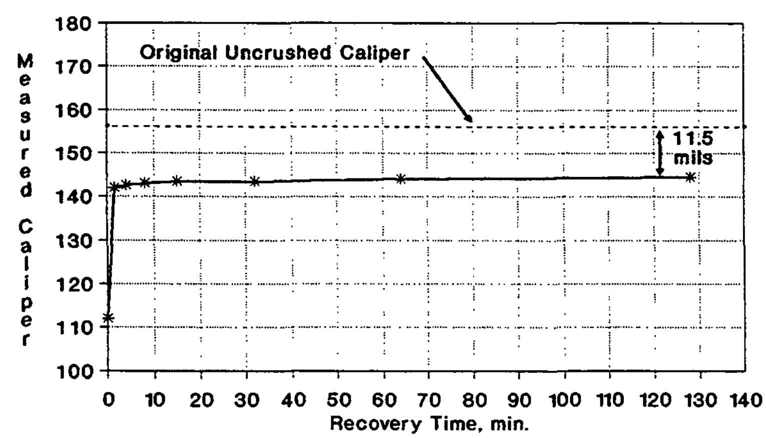
FIGURE 11.13

Rate of Caliper Recovery of Corrugated Board After Crushing By Rubber-To-Steel Roll Nip

Caliper Recovery of Combined Board
Crushed 23.3 mils or 15%
Rubber-to-Steel Crushing Nip, (5)



Caliper Recovery of Combined Board
Crushed 43.7 mils or 28%
Rubber-to-Steel Crushing Roll Nip, (5)



42-26-42, C-Flute
Corrugated Board.

FIGURE 11.14
Effect of Corrugating Conditions and Medium Properties on Combined Board CD Edge Crush Test, (16)

$$ECT = a(A) + b(B) - c(C) - d(D) + e(E)$$

ECT = Edge Crush Test, lb/inch

$r^2 = 0.78$

a = 0.406
b = 0.0201
c = 0.0497
d = 0.00088
e = 0.561

A = CD STFI, lb/inch
B = Pin Adhesion, lb
C = High/Low Flutes Over 4 Mils, %
D = Speed, fpm
E = Medium Basis Weight, lb/msf

FIGURE 11.15
Effect of Medium Elastic Properties on the Retention of CD Crush Strength After Fluting, (1)

$$CR = 1.35 - a(1/A) - (b + c(C))(1/D) - e(1/E) + f(F)(G)$$

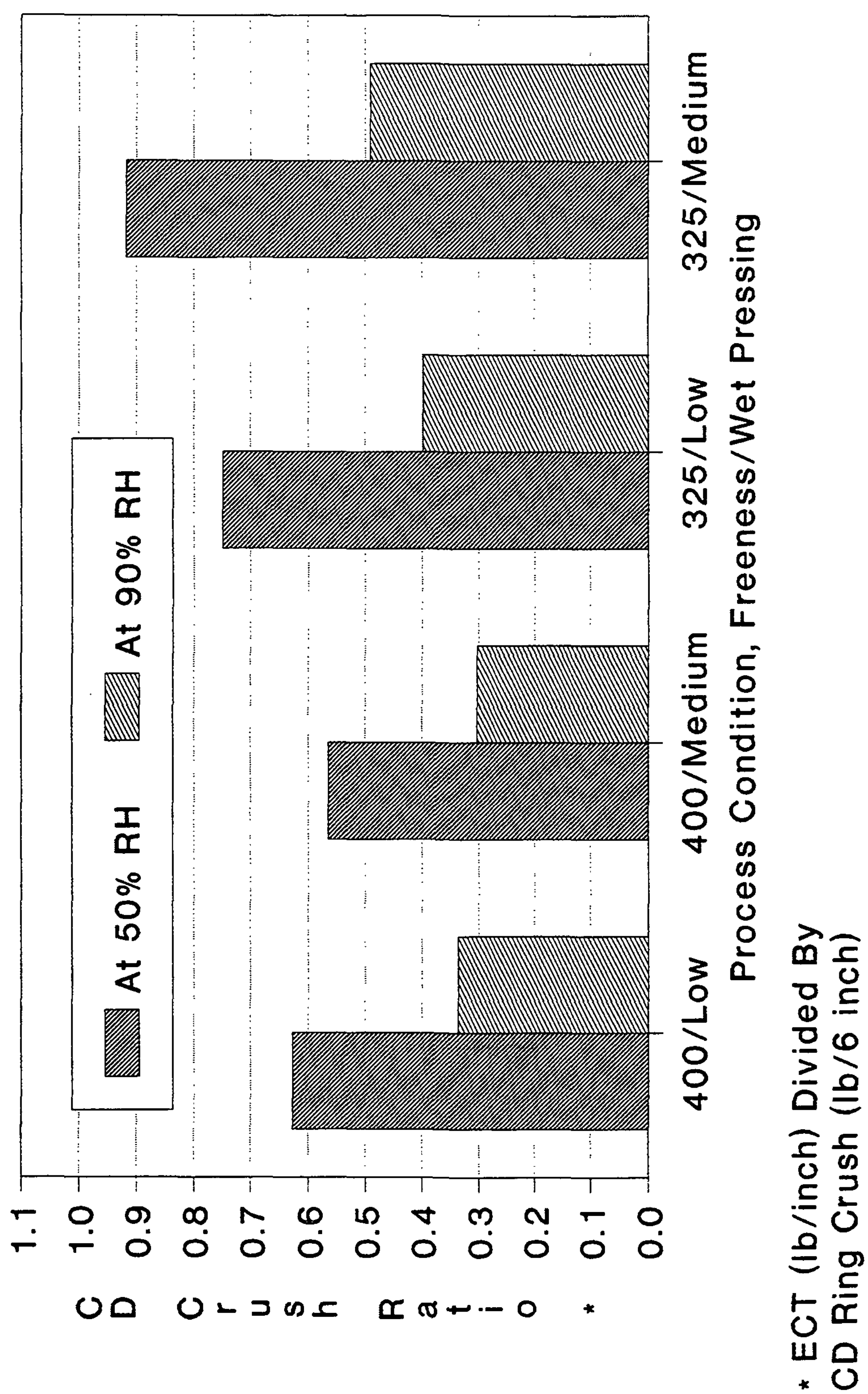
$$r^2 = 0.636$$

CR = (Fluted Edge Crush)/(CD Ring Crush), Both In lb/6 inch

a = 0.385
b = 0.326
c = 0.365
e = 0.0060
f = 0.00037

A = MD Modulus, GPa
C = Density, g/cubic cm
D = CD Modulus, GPa
E = ZD Modulus, GPa
F = XY Poisson Ratio
G = Corrugating Speed, fpm

FIGURE 11.16
Effect of Refining and Wet Pressing on Edge Crush Retention After Fluting for 40 lb/msf Medium. (15)



ing. The term "retention" refers to the combined board ECT strength as compared to the CD ring crush or STFI crush of the unfluted medium rollstock material. A higher ratio or retention means more bang for the buck. The experiments were conducted using Formette handsheets corrugated on a pilot- size corrugator. The data show that a more highly refined (lower freeness) and a more highly wet pressed (more densified) medium retains more of its CD crush strength after fluting. The relative improvement of refining and wet pressing is seen at 90% relative humidity as well as at 50% RH, (15). These results are in agreement with the predicted effects of the regression equation shown in ***Figure 11.15***.

Luckily, more refining of the pulp furnish and more wet pressing on the paper machine also increase the starting CD crush strength of the medium. That is, they increase the pounds of crush strength per lb/msf of medium basis weight, (23). For a given medium basis weight, increased pulp refining and wet pressing increase the CD crush strength of the medium rollstock and increase the degree to which that strength is passed on to the ECT of the combined board.

The next several figures deal with the effect of relative humidity and moisture content on the crush strength of medium. ***Figure 11.17*** shows the relationship between relative humidity and moisture content for a commercial NSSC corrugating medium paper. Both the adsorption and the desorption curves are shown. The medium displays the hysteresis (separation of the adsorption and desorption curves) that is typical for paper, (40).

The effect of moisture content on the CD and MD STFI crush strength of commercial NSSC corrugating medium is shown in ***Figure 11.18***. On average, the medium loses proportionately less CD crush strength than MD crush strength as the paper moisture content increases, (40). The author hypothesizes that this difference is related to the relative effect of moisture on the individual fiber strength versus its effect on the fiber-to-fiber bond strength.

Figure 11.19 compares the effect of moisture content on the crush strength of NSSC medium handsheets to that of Recycled medium handsheets. The compressive strength of the medium was measured using the STFI crush strength method. The data show that there is no difference in the crush strength response of NSSC and Recycled medium to moisture content over the moisture content range of 5% to 15%. Below 5% moisture content, the recycled medium crush strength increases at a faster rate, and above 15% moisture content, the recycled medium loses strength at a slower rate. Both of the medium types attained the same moisture content levels when exposed to the identical humidity and temperature conditions used to condition the samples, (37).

Figure 11.20 compares the effect of corrugating medium moisture content on the compression and tensile properties of the paper. The data show that the compression strength decreases at a faster rate than tensile strength with increasing moisture content up to the 10% moisture content level. Above 10% moisture content, the crush strength decreased at a lower rate than the tensile strength, (37).

Work done at the USDA, Forest Products Laboratory in Madison, Wisconsin, has shown that the stacking life of paper products is more adversely affected by cycling moisture content than by a constant moisture content at the highest end of the cycle. The term "cyclic humidity creep failure" has been used to define this observed physical behavior. Creep failure refers to the gradual deflection of a material with time, when under a compression load, until compression failure occurs. Creep failure is the reason that a corrugated box with a 1000 lb compressive strength cannot remain stacked in a warehouse for an infinite time when the bottom box of the stack has only 500 lb of weight on top of it. Over time, the box will continue to settle down; the side panels of the box will continue to bulge; and one day the box will fail in compression.

Three types of commercial corrugating medium were measured for their cyclic humidity creep characteristics, NSSC, Green Liquor, and Recycled, at the Forest Products Laboratory. Only one random sample of each medium type was tested. All were 26 lb/msf basis weight grades. The results of the study are shown in ***Table 11.1*** in terms of the maximum creep rate (higher is worse), in terms of the hygroexpansivity (sample size changes with RH changes), and the ratio of the two measurements. The ratio will be a constant value if hygroexpansivity is an absolute indicator of the cyclic humidity creep rate expected for different corrugating mediums. The data show that the Recycled medium had the lowest creep rate, followed by the NSSC medium, and then the Green Liquor medium, (4).

Table 11.1. Cyclic Humidity Creep Characteristic of Various Corrugating Medium Types

Corrugating Medium Type	Maximum Creep Rate (m/m per hour)	Hygro- expansivity Strain (m/m)	Ratio (Creep Rate to Hygro. Strain)
NSSC	-0.002644	0.003139	-0.832
Green Liquor	-0.003682	0.004233	-0.863
Recycled	-0.002185	0.003350	-0.632

It must be emphasized that the results in ***Table 11.1*** cannot be used as a generalization about the relative creep performance of the various medium types. Each medium was represented by only one grab sample. The

FIGURE 11.17
Relationship of Relative Humidity and Moisture Content for Corrugating Medium, (40)

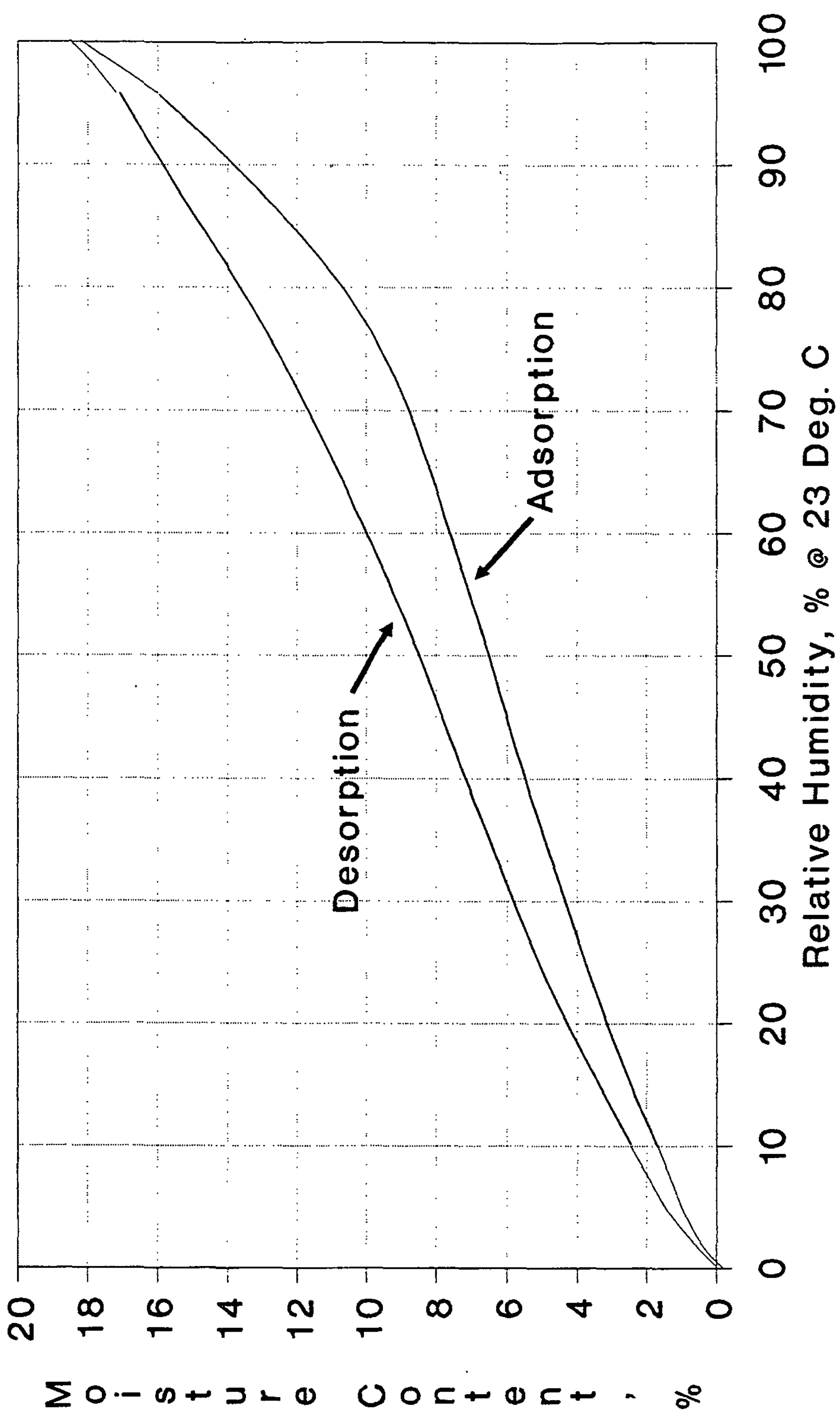
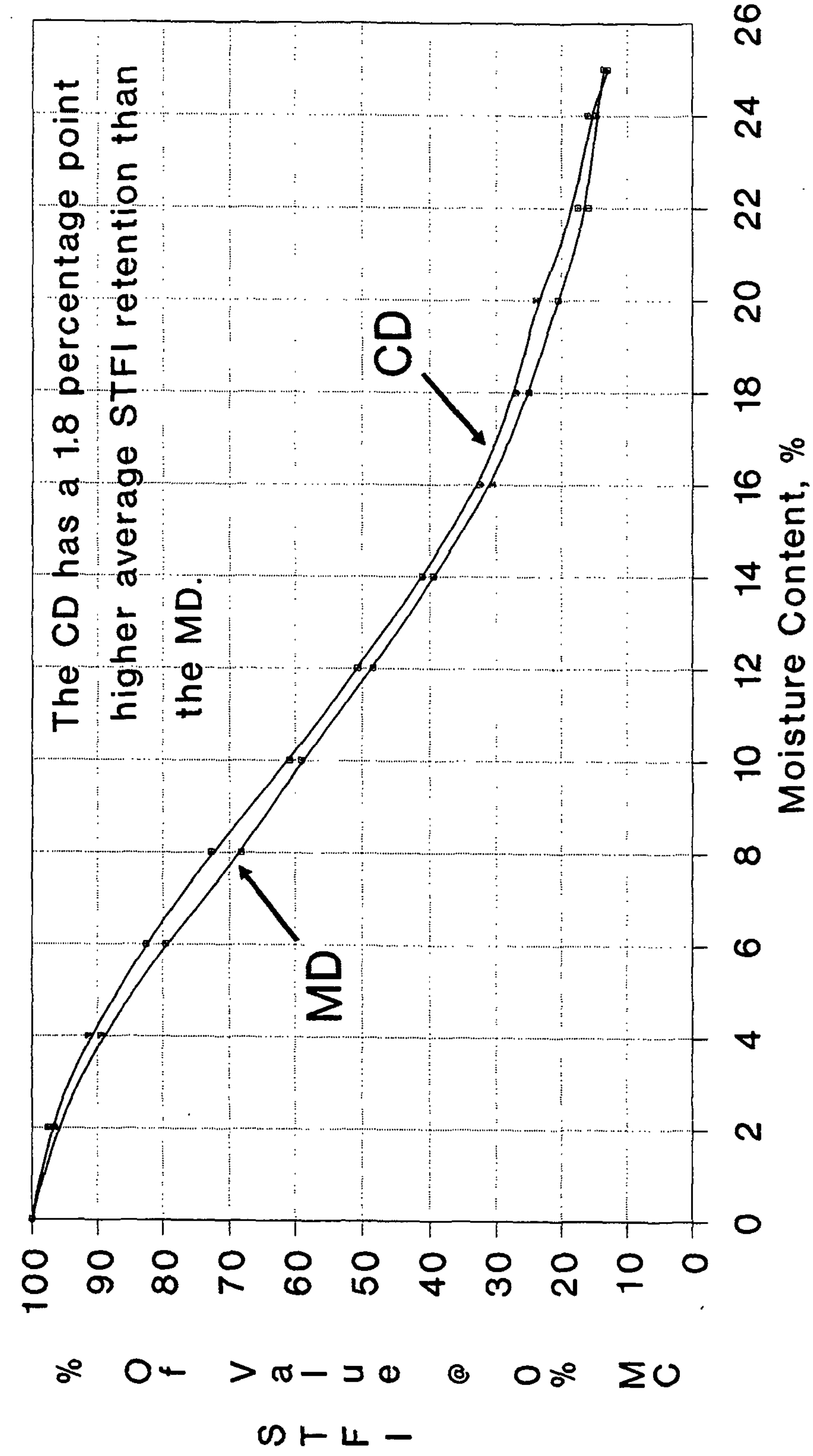


FIGURE 11.18

Effect of Medium Moisture Content on STFI Crush Strength, (40)



Actual Data Points Not Shown

FIGURE 11.19
Effect of Medium Moisture Content
on the CD Compressive Strength. (37)

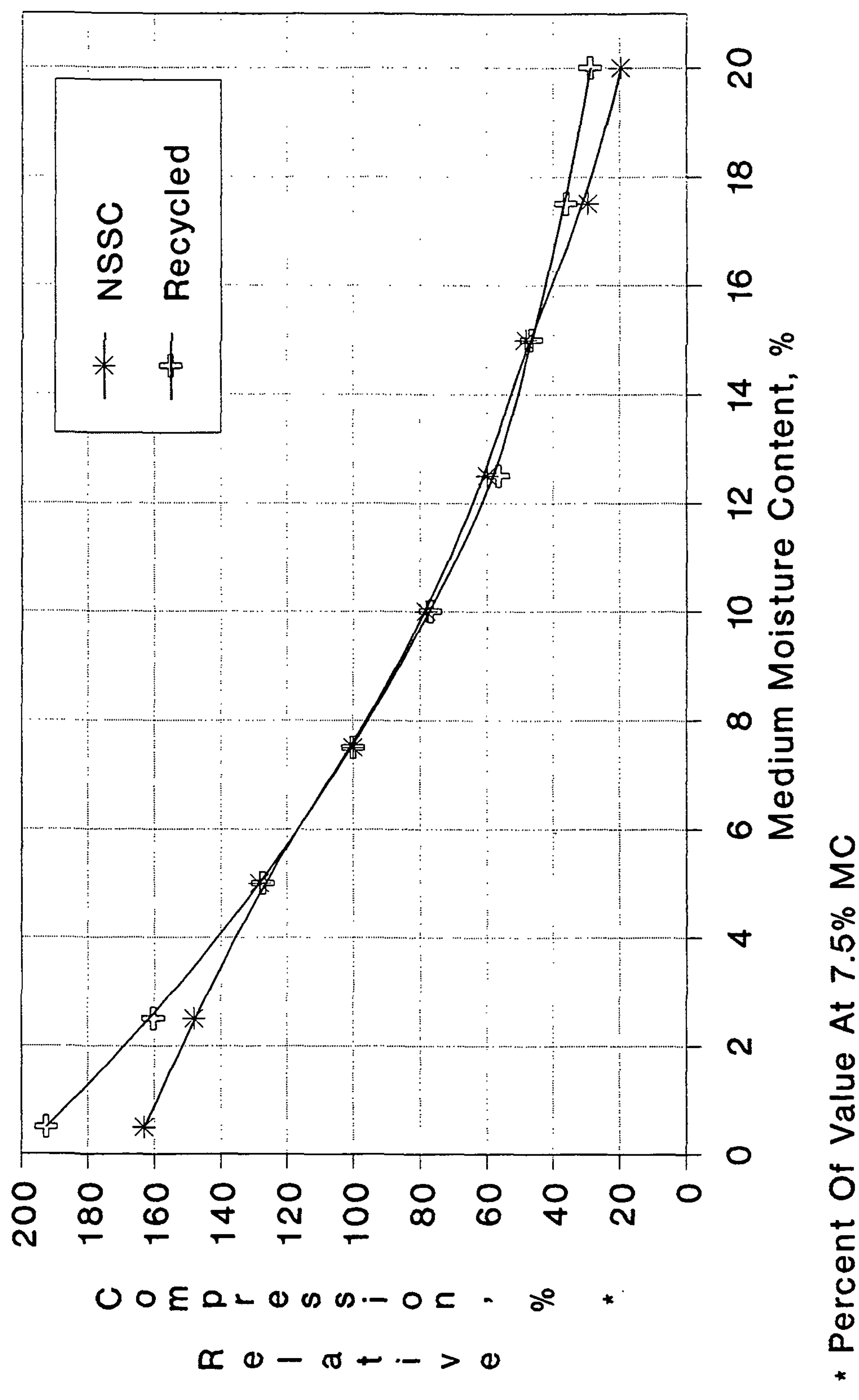
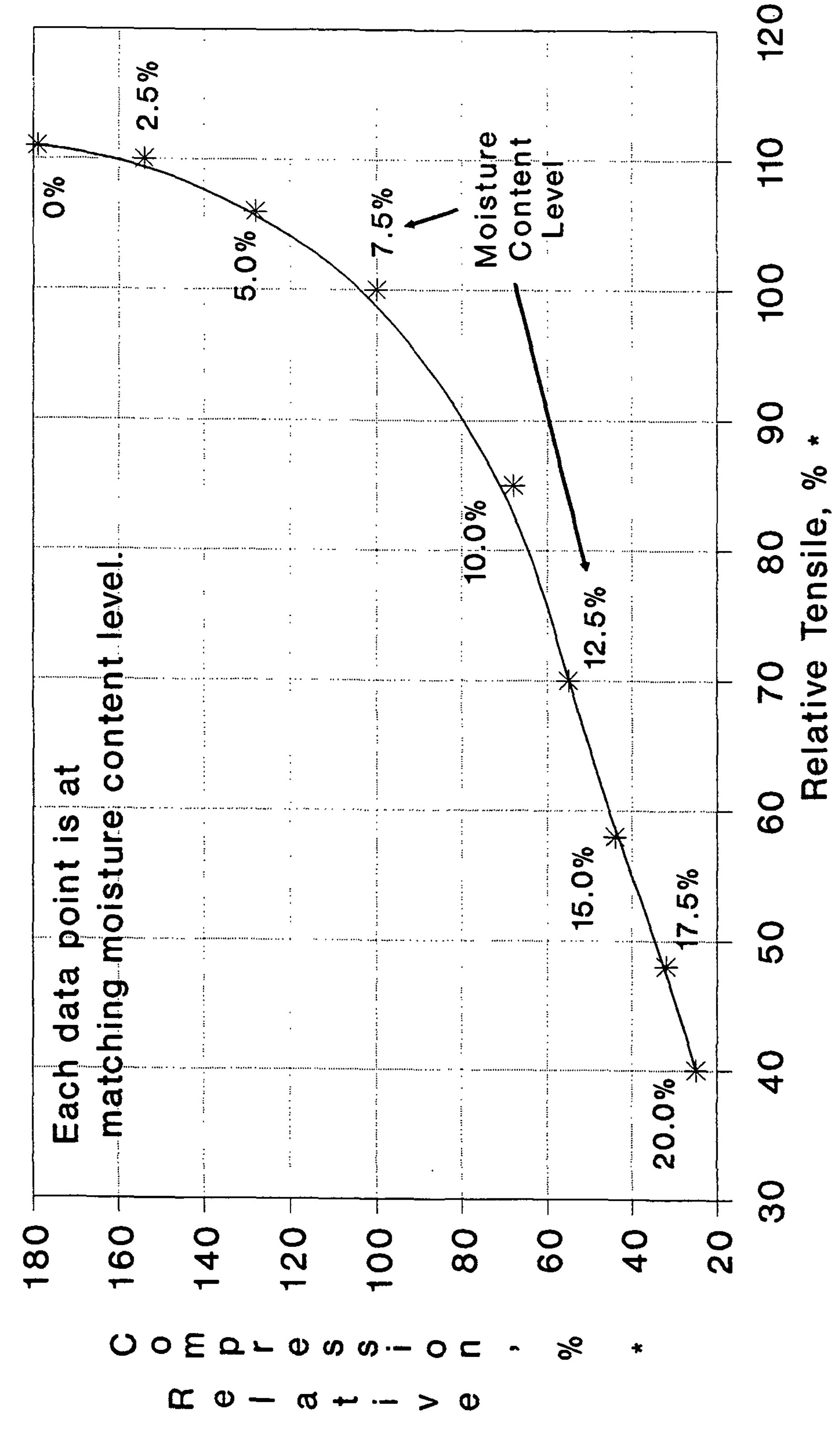


FIGURE 11.20
Comparative Effect of Moisture Content on Medium Tensile and Compressive Strengths. (37)



* Percent Of Value At 7.5% MC

data do indicate, however, that mediums can and do have different cyclic creep characteristics, most likely related to the effect of a wide range of furnish and process variables.

The data presented in this chapter support the following observations concerning the interaction and interrelationship between the corrugating medium and the combined board CD Edge Crush Test.

1. The Edge Crush Test, ECT, is designed to measure the pure edgewise compressive strength of corrugated paperboard.

2. The ECT strength of corrugated board is important because of its effect on the top-to-bottom compressive strength of corrugated boxes.

3. A 10% change in ECT produces a 7.5% change in box compression.

4. The CD edge crush strength of the corrugating medium contributes directly to the CD ECT of the combined board. A stronger compressive strength medium, due to a higher basis weight or to a paper mill strength improvement process change, will increase the ECT of the combined board made from that medium, all other things being equal.

5. Increasing the elastic moduli of the corrugating medium improves the starting strength of the material and the ability of the medium to retain its strength during the flute forming process.

6. Increased medium pulp refining and increased wet pressing of the medium web on the paper machine both increase the elastic moduli of the finished medium paper rollstock.

7. Box plant process variables have a significant effect on ECT. The ECT is adversely affected by flute fracture, high/low flutes, leaning flutes, lower corrugator bond strengths, and crushing of the combined board flutes.

8. The effect of these medium material properties and these box plant process variables on the ECT may partially explain why the industry has not been able to agree on a universal, accurate and precise correlation equation between the medium CD crush strength and the combined board CD ECT.

9. The composite data show that it is not statistically possible, at the 95% probability level, to detect actual combined board crushing of less than 26 mils in a box plant environment by the use of combined board caliper measurements. The combined board regains its caliper too fast to make it a sensitive process control tool.

10. A 25 mill actual crushing level results in a 7.8% reduction in ECT for the largest volume corrugated board grade produced by the industry, 200 lb Test SW or 32 lb/inch ECT SW.

11. A possible alternative approach to controlling flute crushing in the box plant is to measure and control the gap settings at the various pinch points in the process.

Chapter 12

Flat Crush Test

The purpose of testing packaging materials is to provide a basis for predicting the physical properties and the field performance of the final package products, (59). The ultimate goal is to produce a cost-effective package that provides the required protection of the product during the packing, transportation, storage, and consumption phases of its life cycle, (123).

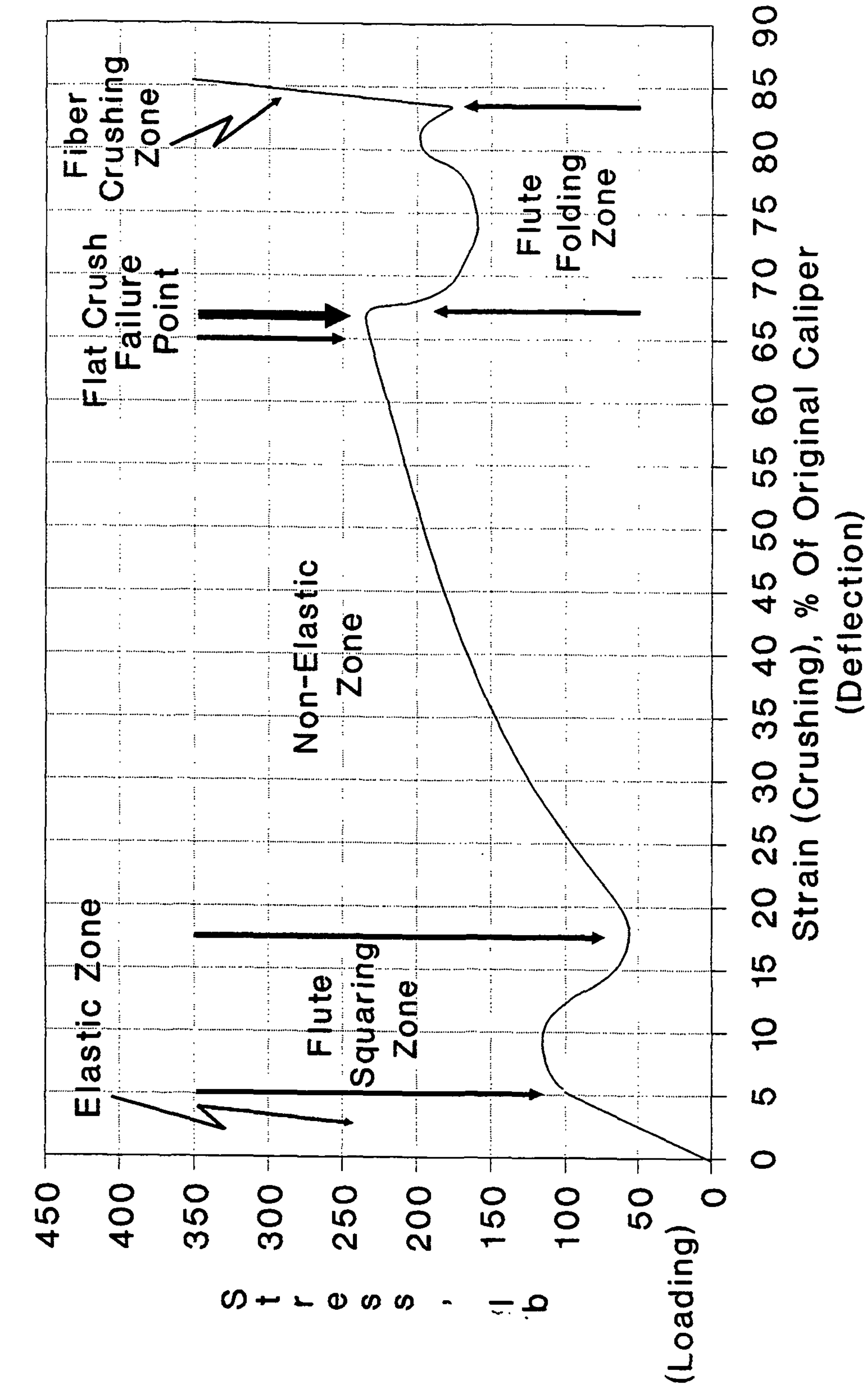
The most distinguishing feature of corrugated paperboard packaging material is the flute structure formed by the corrugating medium, (129). The corrugated board flute structure can be damaged by the crushing forces when it passes between the rollers and belts during the corrugated container making process, (124). These process pinch points include the single-faced web preheater drum at the double-backer (if the flutes are against the drum); the double-backer adhesive application nip; the belted and pressure loaded hot plate and cooling sections of the double-backer; and the various feedrolls, printing units, die cutting units, and folding belts associated with the boxmaking operation, (59, 124, 130). The flutes are also exposed to crushing forces in the package filling line (start and stop forces of the product against the box walls), during package handling (dropping) and during transportation of the filled boxes (acceleration and deceleration of the loads in the truck or rail car).

The Flat Crush Test measures the maximum force that can be supported by the corrugating medium flute structure when the force is applied perpendicular to the combined board surfaces. The flat crush strength is the one corrugated board property discussed in this reference publication that is controlled entirely by the fluted medium portion of the combined board structure. The linerboard facings do not contribute to the flat crush strength in any fashion, except by the effect of the bond sites in keeping the flute spacing. The flat crush strength of corrugated board is influenced by the corrugating roll flute design characteristics of flute size (sidewall height), shape (flute tip radius of curvature and sidewall angle), and the clearances provided between the meshing teeth of the upper and lower corrugating rolls (fluting damage to the medium). A good flute design should provide for the production of a cost-effective flat crush strength. The typical corrugating rolls are designed to accommodate the "standard" 26 lb/msf, 9-point medium, (32, 34, 130). The combined board flat crush strength is also influenced by the properties of the corrugating medium and the corrugating process variable, particularly the moisture content and temperature of the medium at the time that the flutes are being formed, (16, 34).

The Flat Crush Test has long been regarded as an indicator of the strength of the fluted structure in the package and as an indicator of the degree of crushing damage suffered by the corrugated board, (124, 130). Crushing implies damage, and damage implies a quality problem, (130). The corrugated board flute structure can be crushed in processing, lose caliper, feel relatively soft to the hand, and still show no loss in the measured flat crush strength. The Flat Crush Test measures the maximum failure load supported by the medium flutes before the complete collapse of the flute structure occurs, (124). The process crushing damage, prior to actual flat crush failure, affects the quality of the combined board by causing permanent change to the elastic and nonelastic regions of the flat crush stress/strain curve characteristics, (130).

A typical Flat Crush Test stress/strain (load/deflection) curve is shown in ***Figure 12.1*** for a 26 lb/msf A-flute corrugated board grade. The curve exhibits six distinct zones. The first zone is the elastic region where the deflection per unit load is linear and where full caliper, flute shape, and flute strength recovery will occur once the loading force is removed. The second zone is where the initial flute deformation starts. The flute tip starts to flatten, and the sidewalls start to assume a more vertical orientation under the influence of the increasing flat crush load. The third zone is the nonelastic deformation area, where the stress/strain relationship assumes a curved rather than linear shape. This zone represents the continuation of permanent damage to the flute structure. The fourth zone is the flat crush failure point. It is the maximum load that the fluted structure can support. The fifth zone is where the failed flutes keep buckling and

FIGURE 12.1
Flat Crush Stress/Strain Curve
for A-Flute, 26 lb/msf Medium, (124)



folding, and this zone is followed by the sixth zone, where the medium is in full contact with the linerboard, and the force is now attempting to compress the fibers in the paper, (124).

Figure 12.2 shows the relationship between the medium Concora Test and the combined board Flat Crush Test for both B-flute and C-flute corrugated board. The medium basis weights used in the study ranged from 20 lb/msf to 26 lb/msf. The data demonstrate that B-flute yields a higher flat crush strength at a given medium concora strength than does C-flute. This is due to the fact that B-flute has more flute walls per unit area of combined board than C-flute, and the fact that the B-flute sidewall height is shorter than that for C-flute and less prone to buckling under load. The data also show that the flat crush strength does not increase linearly with increasing medium concora strength. A similar curvilinear relationship between the corrugating medium MD Ring Crush Test and Flat Crush Test is shown in ***Figure 12.3*** for commercially produced mediums varying in basis weight from 26 lb/msf to 54 lb/msf, and fluted on a pilot-size corrugator, (39). These two experiments indicate that heavier basis weight mediums lose more flat crush strength during fluting. This can be attributed to the increased flute sidewall damage caused in the thicker medium by the reduced relative clearance between the meshed teeth in the upper and lower corrugating rolls, (15, 34, 39, 73, 82, 130).

The medium Concora Test is used to measure the flat crush potential of medium rollstock before actual corrugating. It was developed as a tool to predict the flat crush strength expected in the final combined board. The Concora Test involves the simulation of the commercial corrugating operation by using a small, bench top corrugating unit. The half-inch wide sample of medium is fluted, faced with an adhesive covered tape, and crush tested. In actuality, there are several significant differences between the Concora Test and commercial corrugating. The Concora Test uses A-flute-shaped heated corrugating gears; the medium is not preheated or presteamed before being fluted; and the corrugating is done at an extremely slow speed, (15).

Figure 12.4 shows the relationship between the MD STFI crush strength of the sidewall areas of the fluted medium and the flat crush strength of the combined board. The study used commercial 26 lb/msf semichemical and recycled mediums combined on a pilot-size corrugator. The data show a linear relationship between the two test values over the range of strength covered by the study. This indicates that both tests reflect the fluting damage that occurred during corrugation. Comparison of the fluted and unfluted MD STFI crush strengths shows a 30% to 40% MD strength loss due to fluting. It is hypothesized that the effect is due to shear forces that disrupt the fiber-to-fiber bonding in the corrugating medium, (30, 95).

Figure 12.5 shows a regression equation relating the flat crush strength of the combined board to the strength of the medium and to corrugating process variables. The data show that the combined board flat crush strength is related to the medium concora crush strength, but, that the amount of concora strength retained after fluting is controlled by the corrugating process variables of medium moisture content and medium temperature at the point in time when the flutes are actually being formed. A higher medium rollstock moisture content, a higher medium web temperature, and more presteaming moisture addition to the medium all improve the retention of flat crush strength during fluting, (16, 95). The specific influence of the medium rollstock moisture content and moisture added to the medium web by the steam showers is shown in ***Figure 12.6***. The experimentation was done using commercially produced medium and a pilot-size corrugator. Between the range of 5% to 13% moisture content, a 1 percentage point increase in the medium web moisture increases the flat crush strength by an average of 1 psi or 2.8%, (16).

The effect of the medium temperature on flat crush retention during fluting is shown in ***Figure 12.7***. The experiment was done using handsheets and a modified concora test instrument. The data show that, on average, a 20 deg.F. increase in temperature increases the flat crush strength retention during fluting by 1.25 lb or 3.3%, (95).

With these effects, it is no wonder that the data in ***Figures 12.2 and 12.3*** show that increased medium basis weight does not always translate into higher combined board flat crush strength. Neither experiment was designed to minimize the strength loss due to fluting of the heavier weight medium materials. Most corrugating rolls and corrugator process conditions are geared to 26 lb/msf or lower basis weight medium, (15, 32, 34, 39, 73, 82, 130).

The effect of medium properties on the retention of flat crush strength during fluting is shown in ***Figure 12.8***. The experiment was conducted using Formette handsheets, ranging in basis weight from 26 lb/msf to 40 lb/msf, fluted on a pilot-size corrugator. The data indicate that the flat crush retention is improved by a corrugating medium material with a higher density, a lower basis weight, a lower MD elastic modulus, and a higher ZD (thickness direction) elastic modulus, (29, 33).

One objective at the paper mill is to improve the flat crush cost-effective quality of the corrugating medium. However, that quality improvement must carry through to the combined board after high-speed corrugating if it is to have true commercial value, (30). ***Figure 12.9*** shows the influence of paper mill pulp refining and paper machine wet pressing on the retention of flat crush strength during fluting. The experiment used Formette

FIGURE 12.2
Relationship Between Medium Concora and Combined Board Flat Crush. (73, 82)

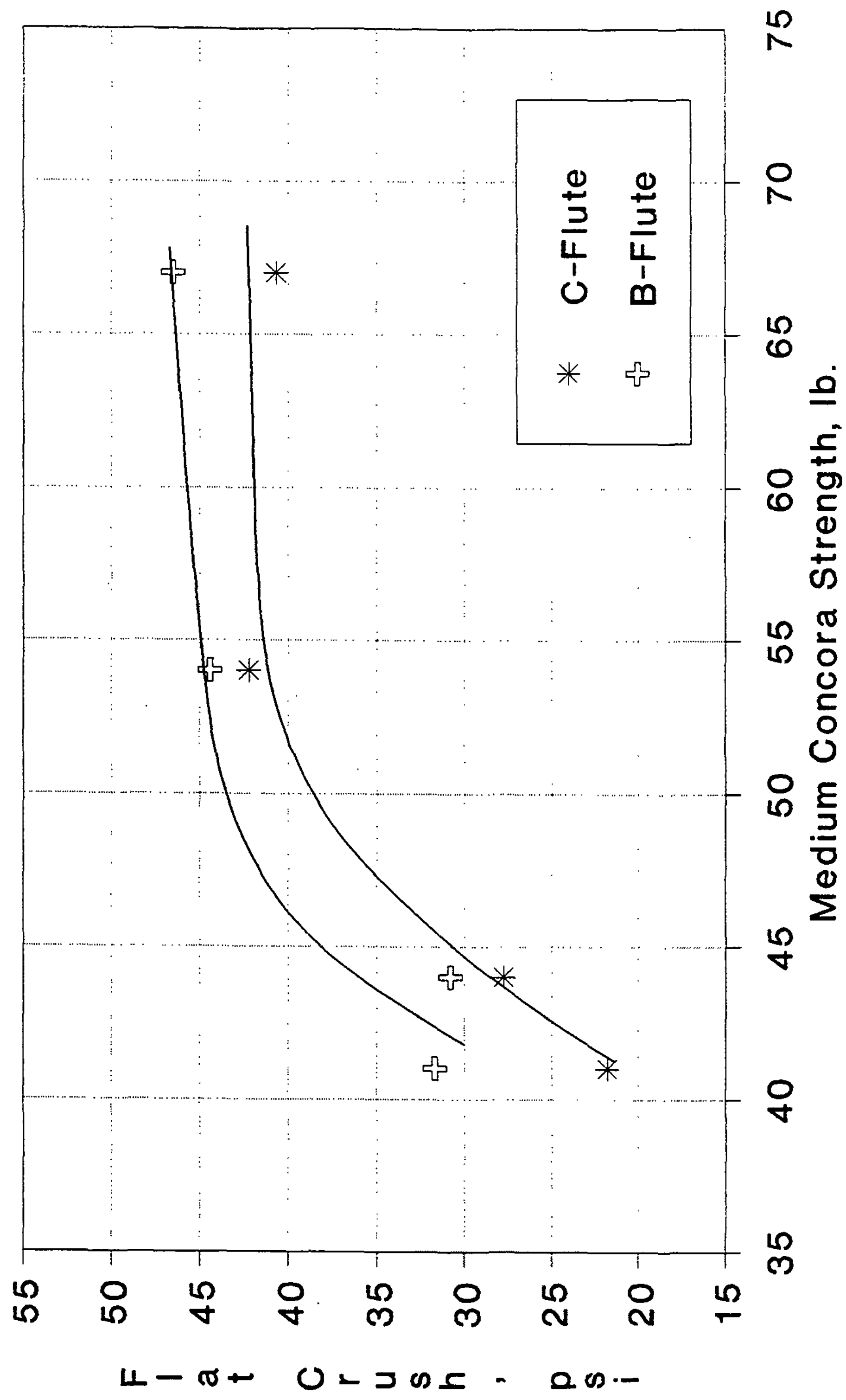


FIGURE 12.3
Relationship of Medium MD Ring Crush to Combined Board Flat Crush, (39)

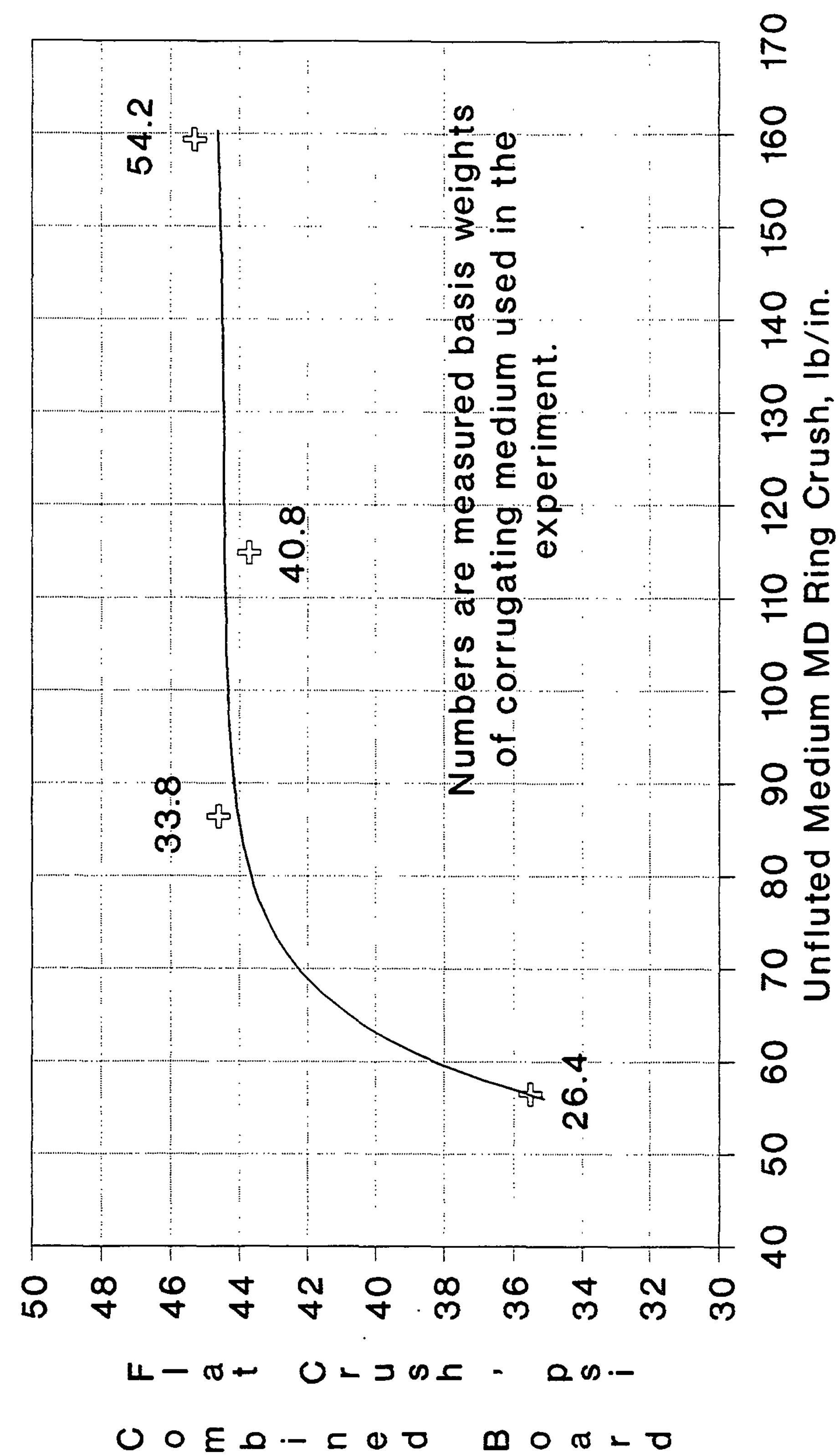


FIGURE 12.4
Relationship of MD STFI Compression of Fluted Medium and Flat Crush, (30)

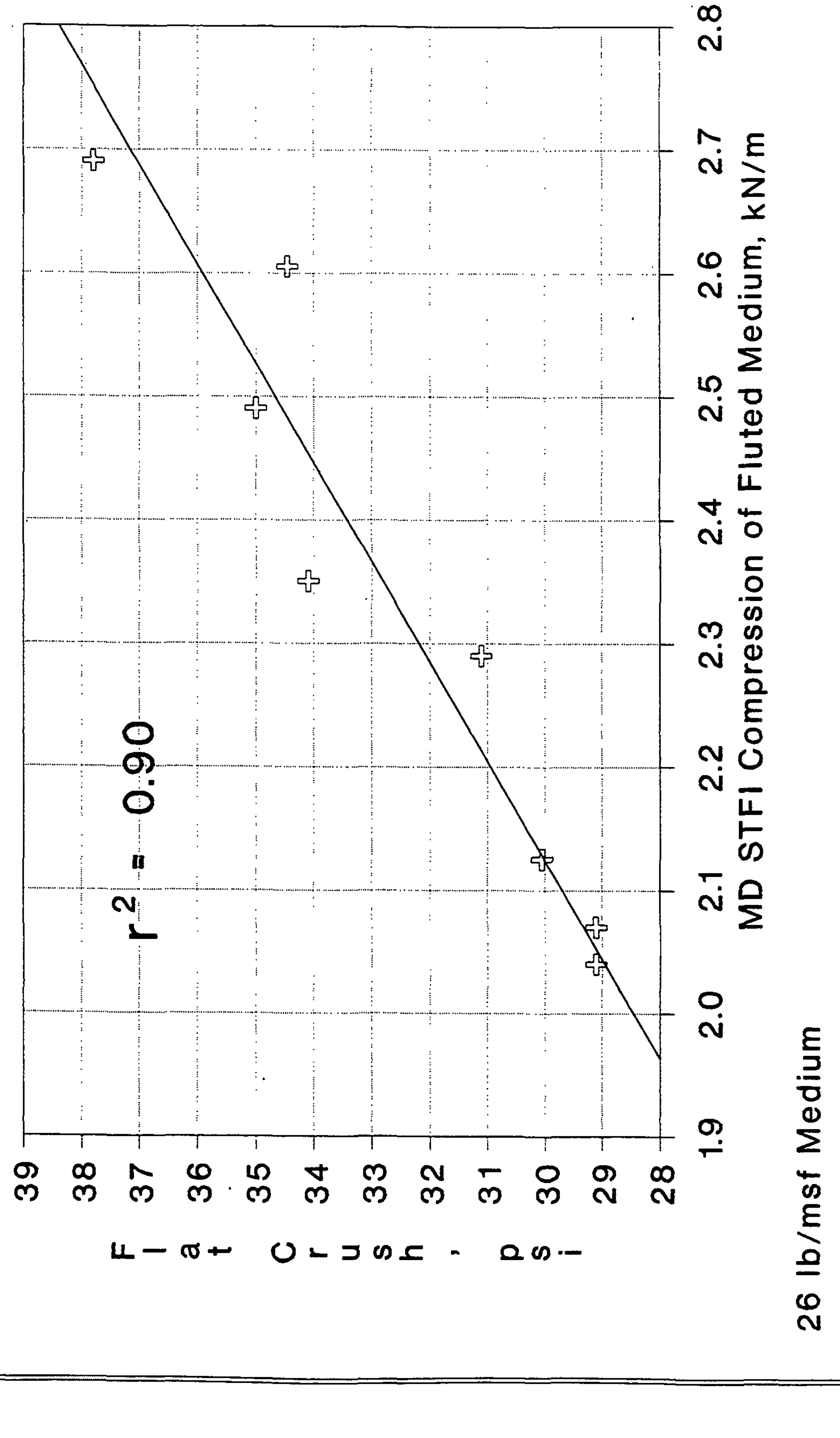


FIGURE 12.5
Effect of Corrugating Variables and Medium Properties on Flat Crush, (16)

$$FC = a(A) + b(B) - c(C)^2 + d(D) + e(E)^2 + f(F) - g(G)^2 + h(H) - 37.5$$

$$r^2 = 0.82$$

a = 0.00168	A = Speed, fpm
b = 1.58	B = Nip Moisture Content, %
c = 0.0443	C = B
d = 0.292	D = Nip Temperature, Deg.F
e = 0.00088	E = D
f = 1.35	F = Roll Moisture Content, %
g = 0.0854	G = F
h = 0.555	H = Concora, lb

FC = Flat Crush, psi

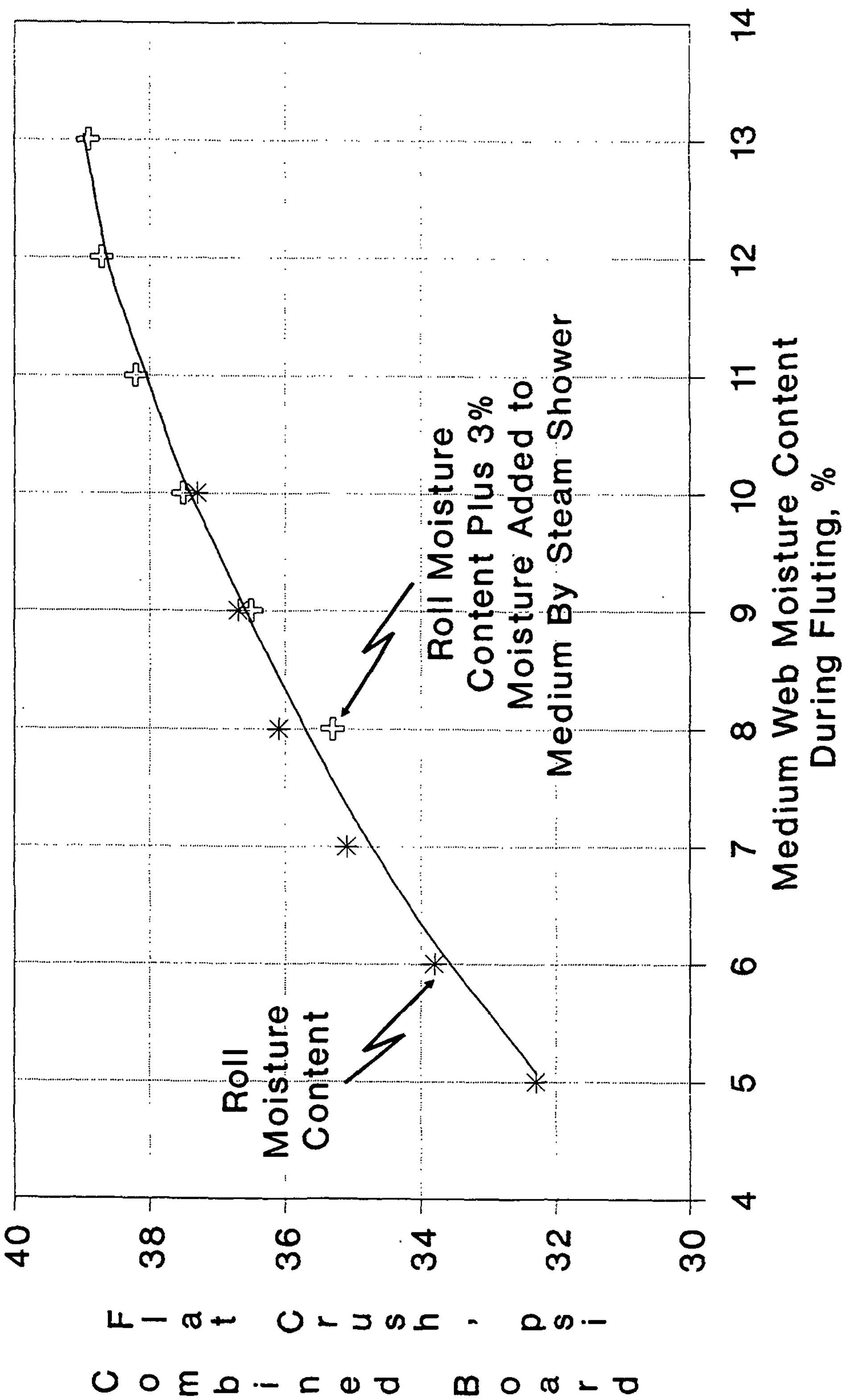


FIGURE 12.6
Effect of Medium Web Moisture Content at Corrugating Roll Nip on Flat Crush, (16)

FIGURE 12.7

Effect of Fluting Gear Temperature on Medium Concora Strength, (95)

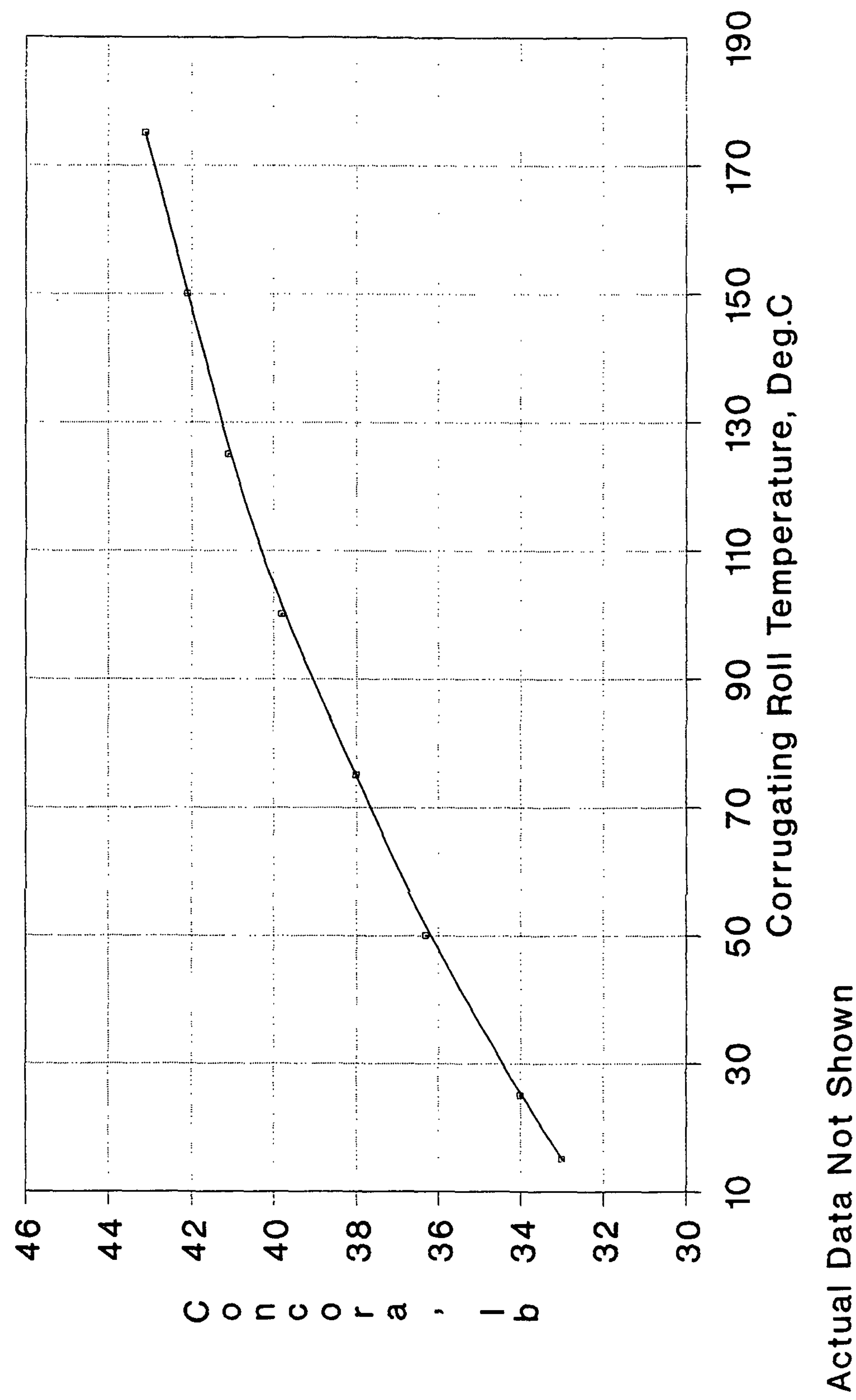
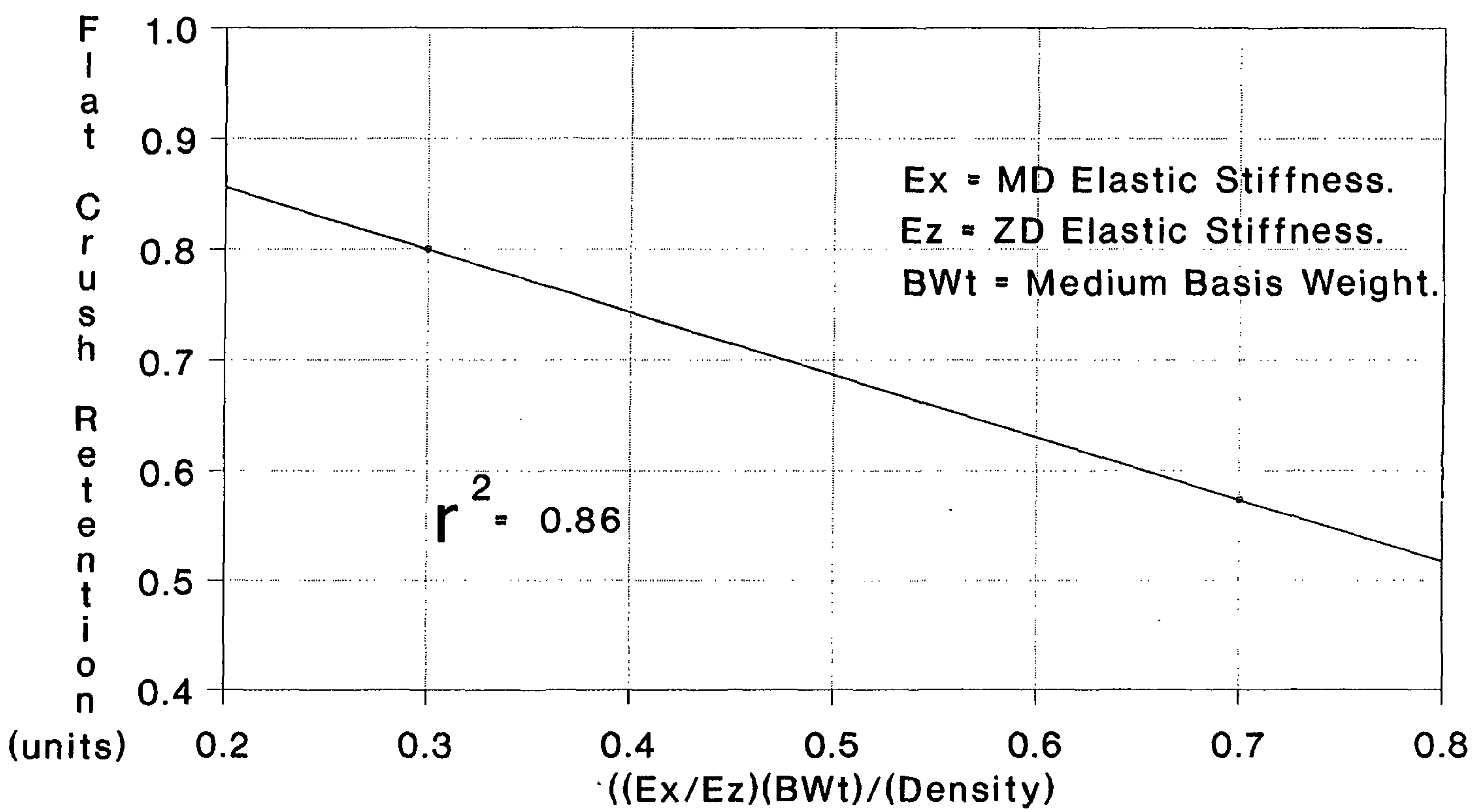
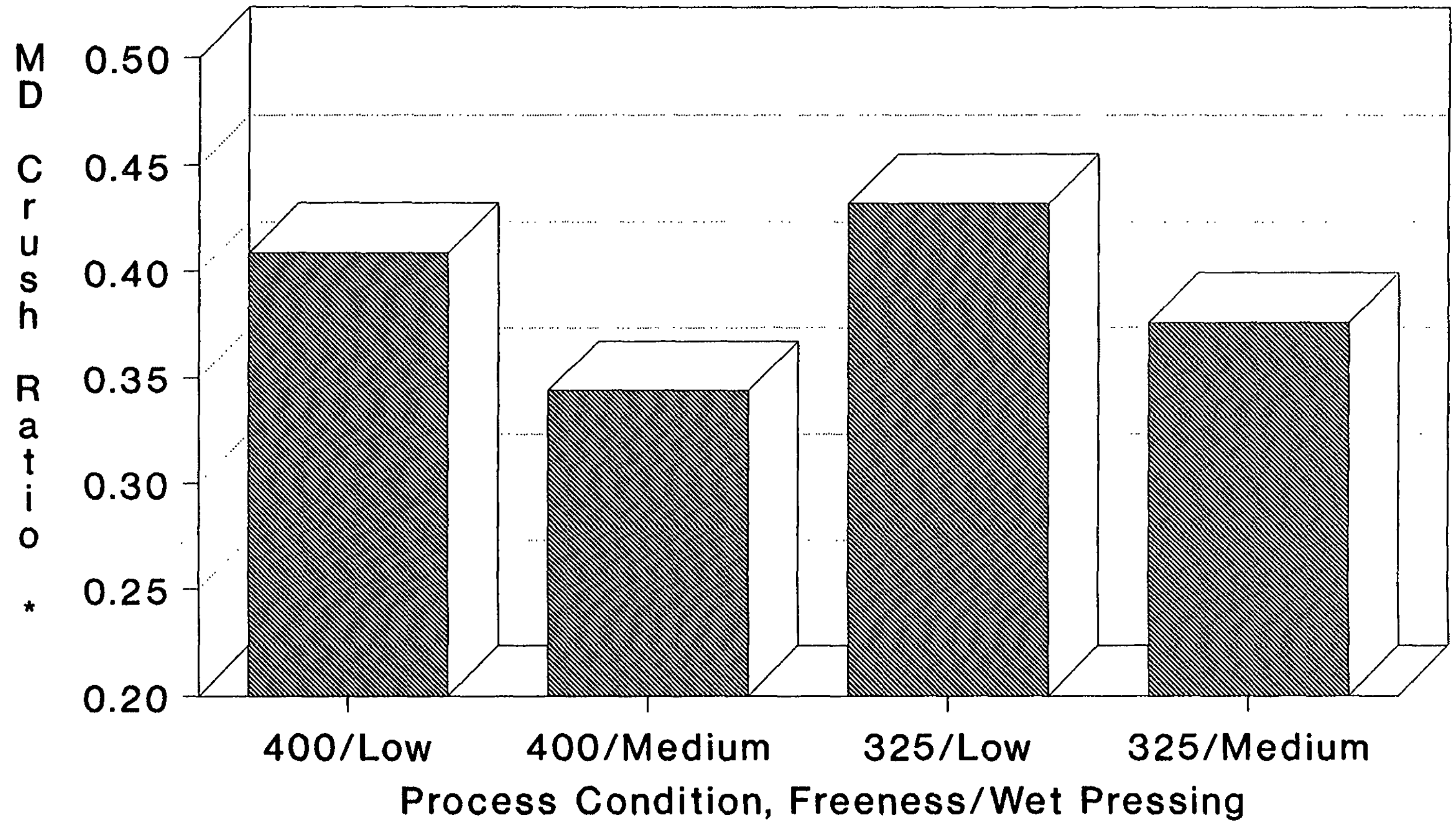


FIGURE 12.8
Effect of Medium Properties on the Flat Crush Strength Retention After Fluting. (29)



Actual Data Points
Not Shown

FIGURE 12.9
Effect of Pulp Refining and Wet Pressing on Flat Crush Retention After Fluting 40 lb/msf Corrugating Medium, (15)



* Flat Crush (psi) Divided By Concora Crush (lb)

handsheets and a pilot-size corrugator. The data indicate that lower wet pressing and increased pulp refining are beneficial, (15). Others have concluded that increased wet pressing is beneficial because of the reduced caliper of the medium, (23, 24, 26, 39). Both increased refining and increased wet pressing benefited the CD edge crush strength retention during fluting, ***Figure11.16*** in Chapter 11. This is, then, an area that may require controlling the papermaking process to obtain a reasonable balance between two combined board properties important to package performance, Edge Crush Test and Flat Crush Test.

The effect of fractured flutes on flat crush strength is shown in ***Figure 12.10***. The degree of fracture represented by the data is very slight, being just at the breakpoint between fractured and unfractured medium flutes. This level of defect reduces the flat crush strength by almost 10%, (129).

The effect of crushing of the combined board flutes on flat crush strength is shown in ***Figure 12.11*** for A-flute board made with 26 lb/msf medium. The data show that a measured crush of 5 mils reduces the flat crush strength by 5%, (130). However, it should be noted that a measured crush of 5 mils represents an actual crush of approximately 33 mils, (5).

The degree of measured crush caused by a given nip force is affected by the concora strength of the medium, as shown in ***Figure 12.12***. The experiment used four commercially produced corrugating mediums ranging in basis weight from 20 to 26 lb/msf. The combined board was produced on a commercial corrugator and crushed in the laboratory using a rubber-to-steel roll nip. The data show that lower concora strength mediums are more susceptible to crushing under conditions where the rubber-covered nip roll can compress and reduce the crushing done to the corrugated board, (73, 82). With steel-to-steel rolls, where the gap is mechanically set, all corrugated board is equally crushed, regardless of its flat crush stiffness, (24). The use of compressible rubber rolls is the basic concept of the so-called "no-crush" systems being sold commercially to box plants. The data also show that higher crushing forces cause larger permanent caliper losses (flute deformation) in the combined board. The difference between B-flute and C-flute effects is shown in ***Figure 12.13***. B-flute combined board has a higher flat crush strength than C-flute board because of the closer spacing of the flutes and because of the lower height of the sidewalls of B-flute. This gives B-flute a greater resistance to the crushing forces. Similarly, A-flute is less resistant to crushing than C-flute, (73, 82).

Figure 12.14 also shows data on the effect of flute crushing on flat crush strength. These data do not agree with the previous data, (124). No explanation was given in the publication, and the author has no rationale to offer except that there may be some technical errors in these data.

Measured caliper and measured Flat Crush Test are poor indicators of the actual degree of flat crush strength damage caused by crushing of the combined board. They do not accurately reflect the permanent changes that have occurred to the characteristics of the flat crush stress/strain curve, ***Figure 12.15***. Combined board can be crushed up to 40% without any major change to the measured, maximum flat crush strength or to the deflection of the sample at Flat Crush Test failure. Yet, the elastic flat crush strength zone of the material has been destroyed, and the non-elastic zone severely deformed. These changes can cause the board to feel soft and to be less effective in its cushioning properties, (59, 124).

Figure 12.16, top graph, compares actual combined board flute crushing to measured crushing. The data show that caliper measurement in a box plant is a poor indicator of actual crushing and crushing damage. The rapid rebound in caliper after crushing, more than 90% recovery within the first minute after the crushing force is removed, and the relatively high variability in combined board caliper measurements indicate that actual crushing below 25 mils will not be statistically detectable at the 95% probability level, in the best of corrugated box plants, (5).

Figure 12.16, bottom graph, also shows that the relationship between actual and measured crush depends on the nature of the nip point. The use of rubber-covered rolls that can compress and absorb some of the crushing deflection reduces the actual corrugated board crushing, (130). With steel-to-steel rolls, where the gap is mechanically set, all corrugated board is equally crushed, regardless of its flat crush stiffness, (24).

Figure 12.17, top graph, shows that a higher basis weight medium has a higher caliper recovery than a lower basis weight medium. This effect can be attributed to the greater flute rigidity provided by the heavier basis weight medium. ***Figure 12.17***, bottom graph, also shows that multiple crushing of the same area of the combined board results in a higher degree of nonrecoverable caliper loss, (130).

In summary, the technical information presented in this chapter supports the following observations concerning the flat crush strength of corrugated board.

1. Corrugated board is exposed to numerous flat crush stresses during the manufacture of the package and during the field use of the package.

2. The Flat Crush Test measures the maximum load that can be supported by the corrugating medium flutes before total destruction of the flute structure occurs. The characteristics of the entire flat crush strength stress/strain curve are more important to package performance than just the maximum failure strength.

FIGURE 12.10
Effect of Fractured Flutes on Combined Board Flat Crush Strength. (129)

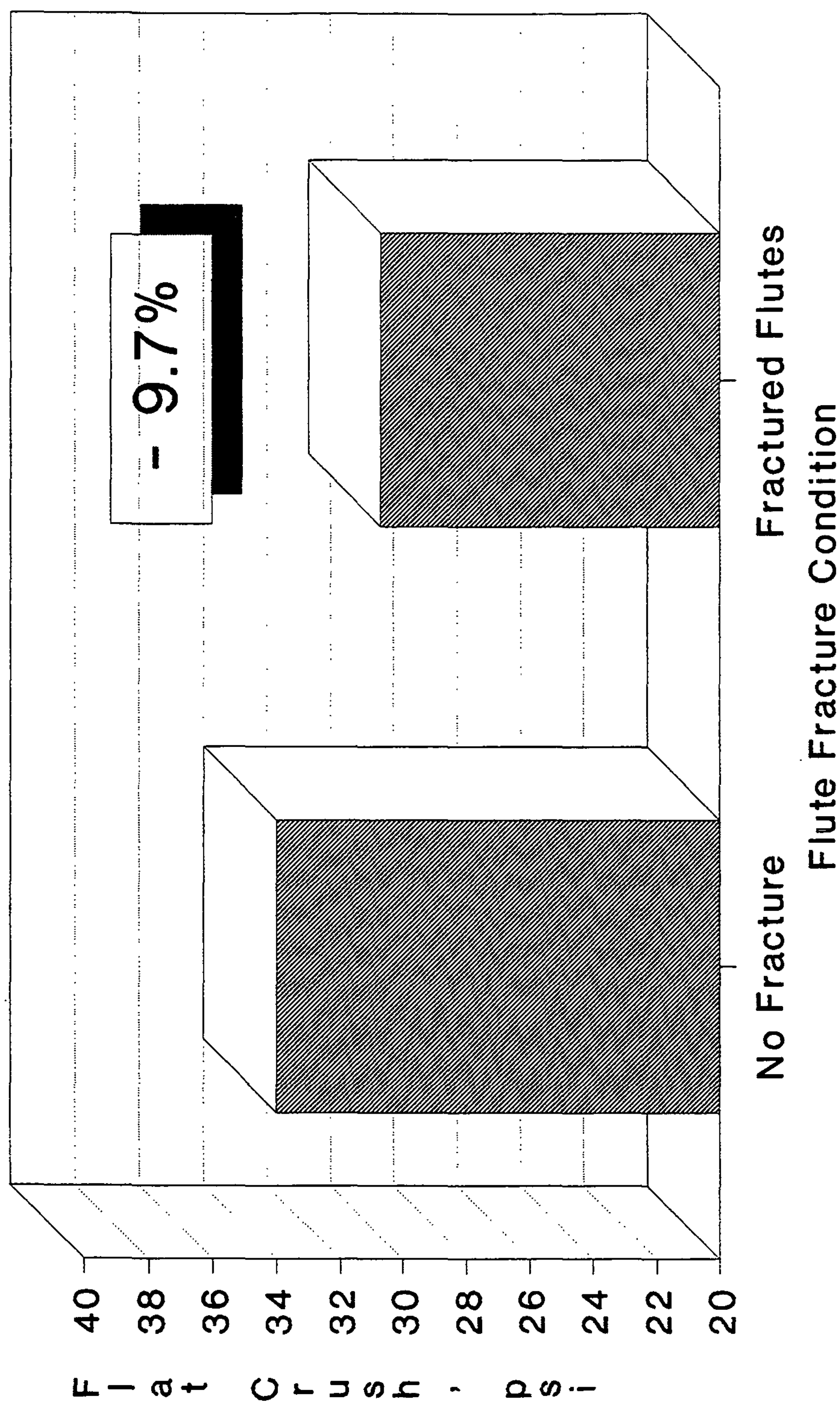


FIGURE 12.11
Effect of Flute Crushing on Combined Board Flat Crush Strength. (130)

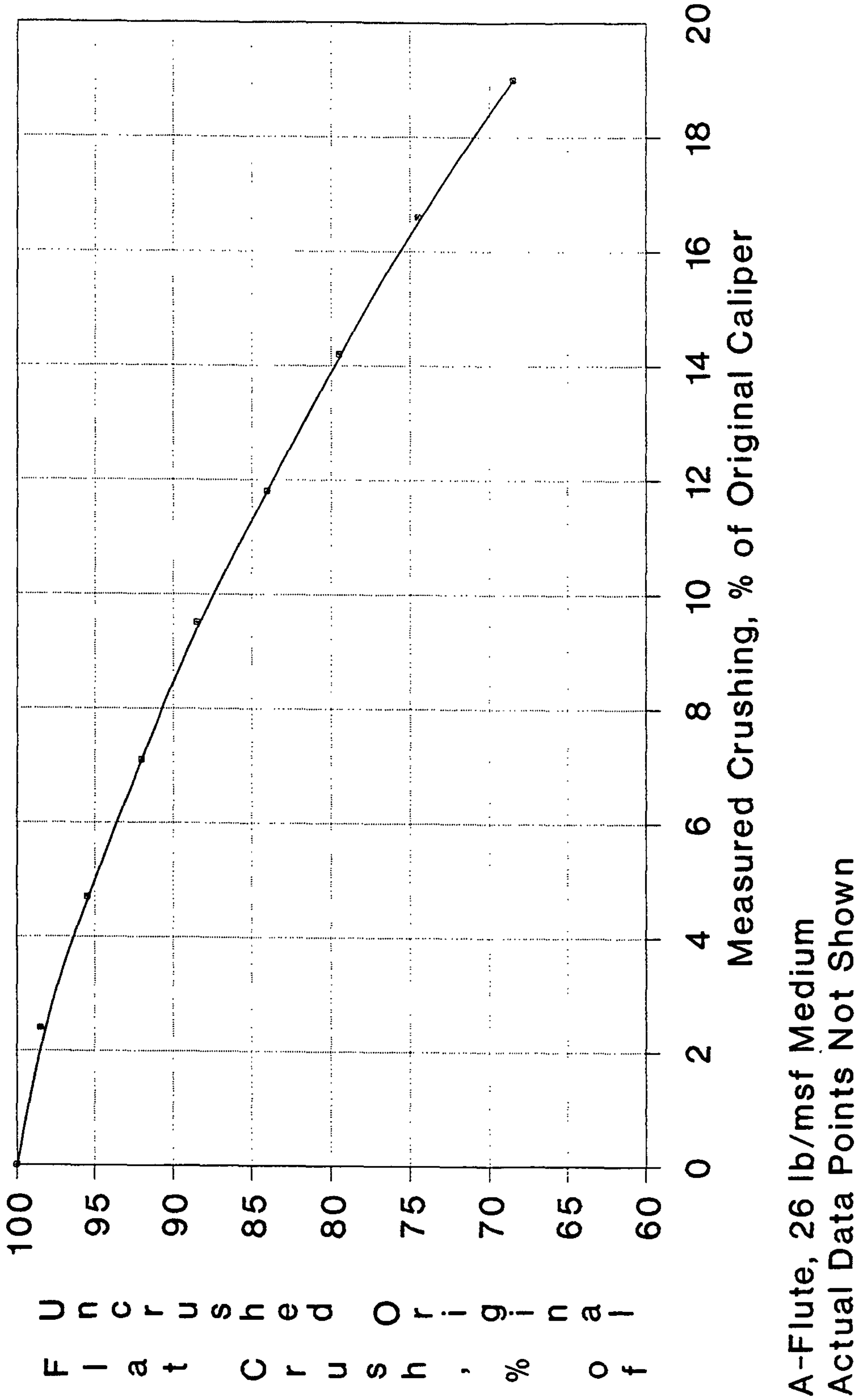
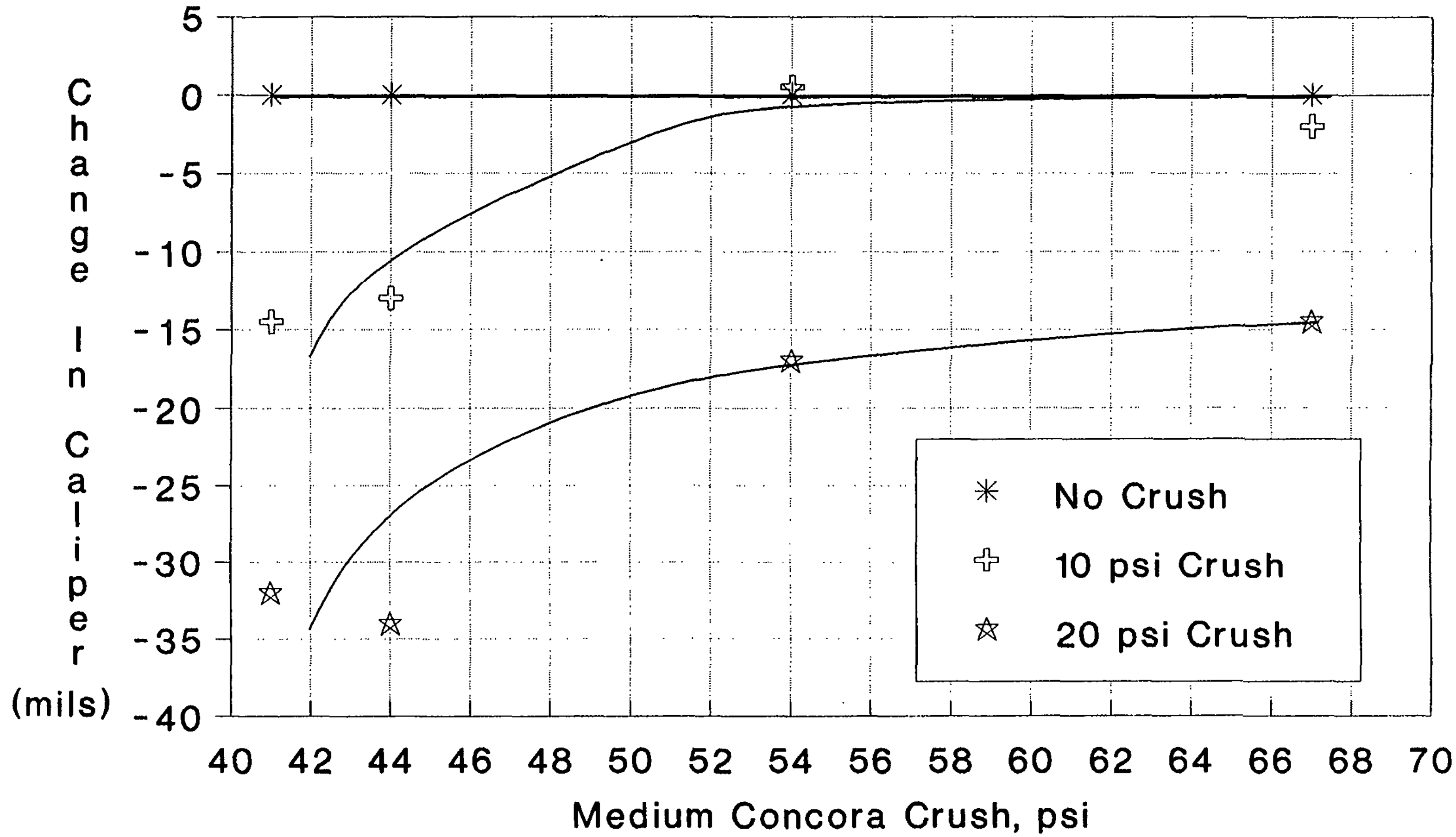
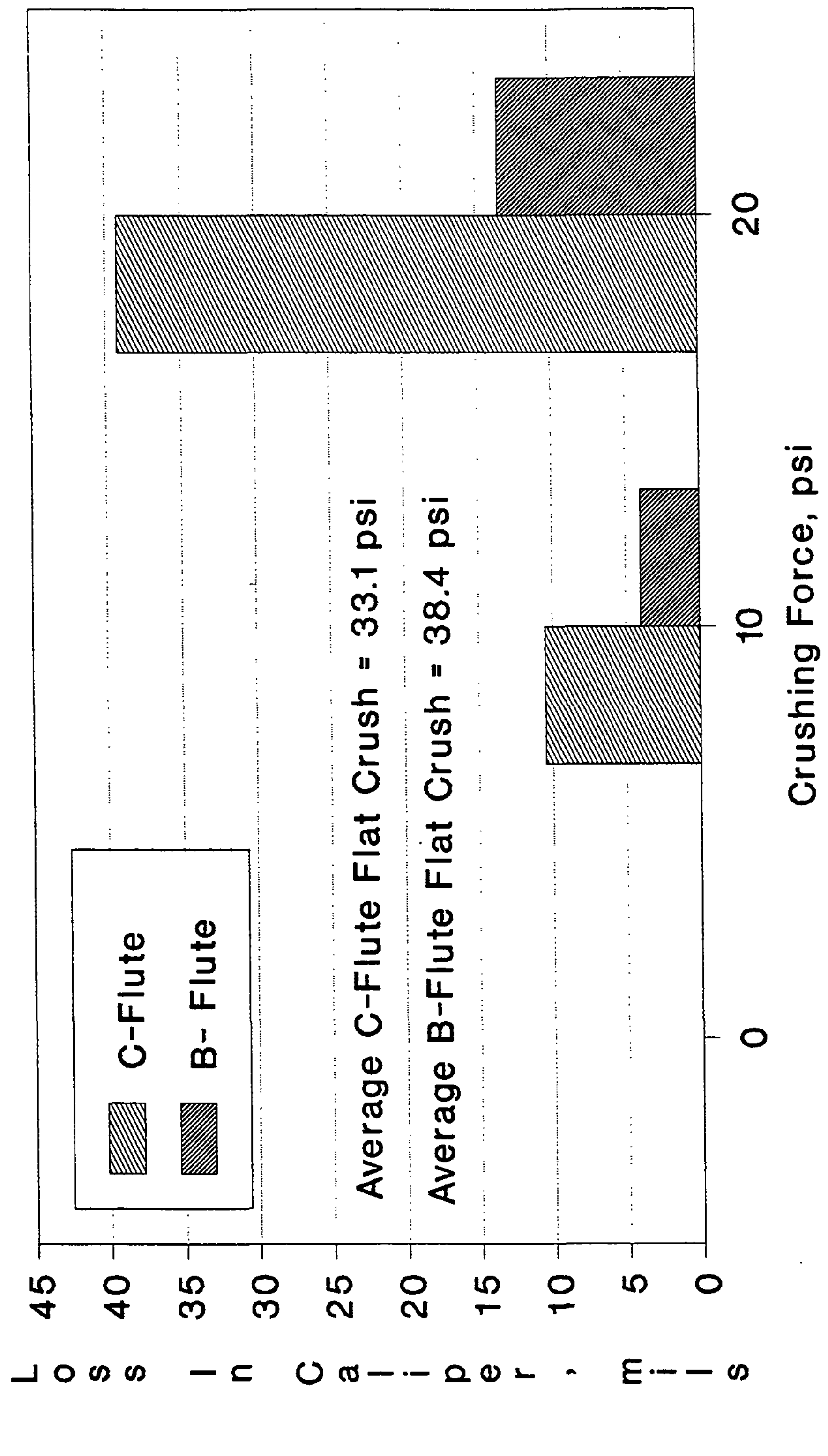


FIGURE 12.12
Effect of Medium Concora Strength on Nonrecoverable Crushing of Flutes, (73)



Average of A & B-Flute.

FIGURE 12.13
Effect of Flute Size on
Nonrecoverable Caliper Loss, (73)



Average Of Four Different
Concora Crush Strength Mediums.

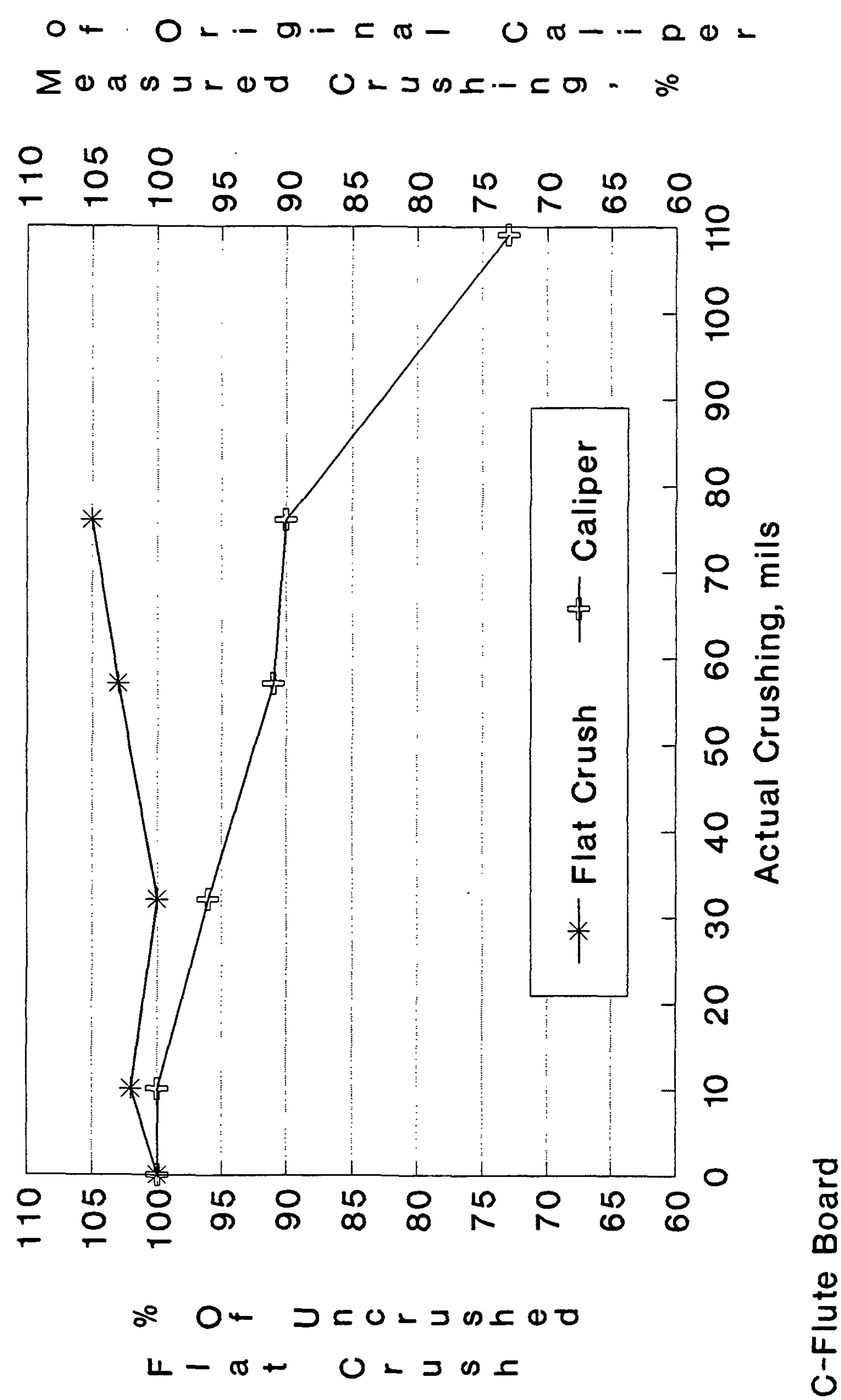
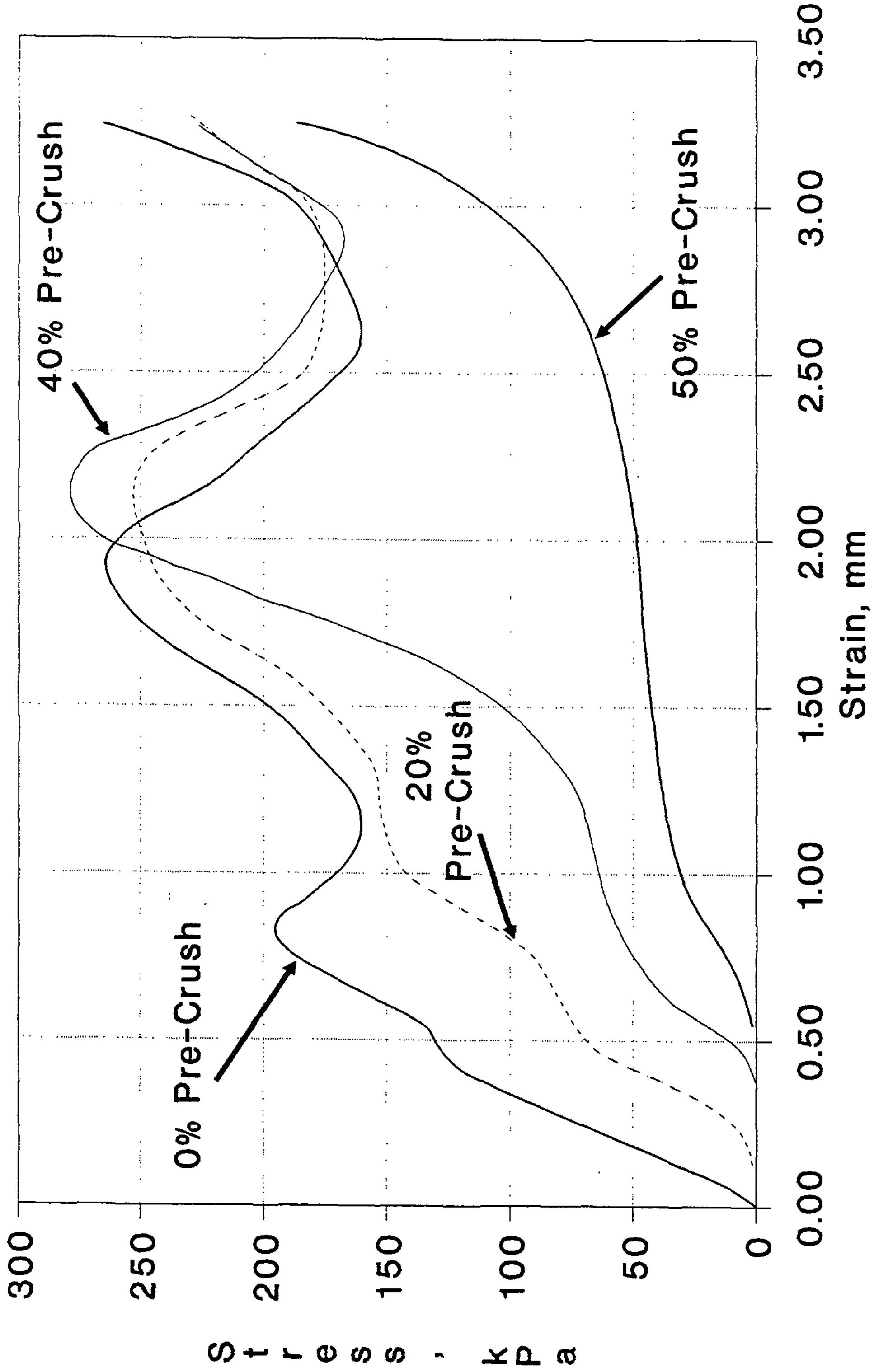


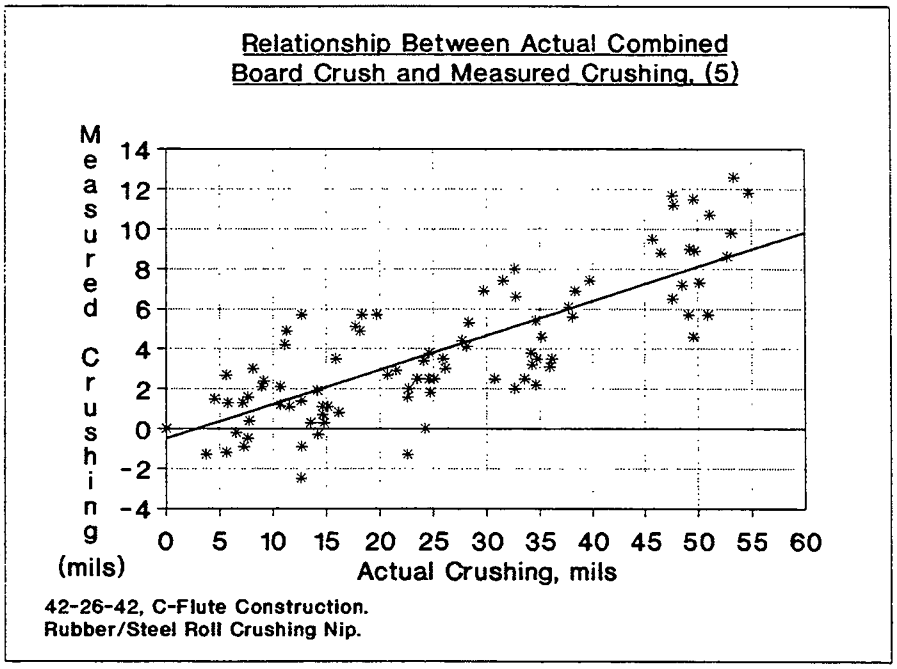
FIGURE 12.14
Effect of Combined Board Crushing on Flat Crush Strength, (124)

FIGURE 12.15
Flat Crush Stress/Strain Curves: Effect of Combined Board Precrushing. (59)



C-Flute Corrugated Board.

FIGURE 12.16
Effect of Combined Board Crushing on Post-Crushing Combined Board Caliper



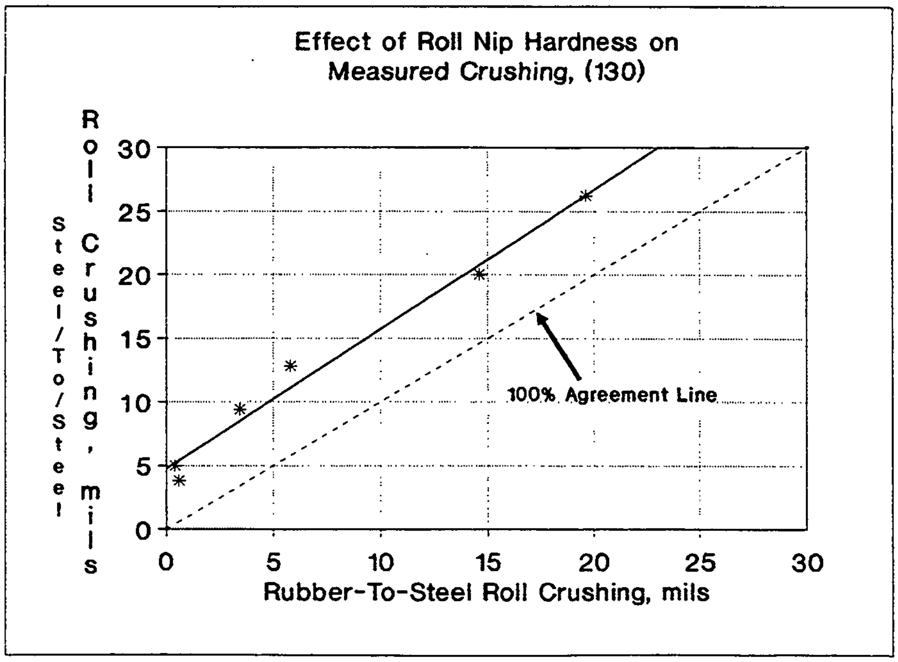
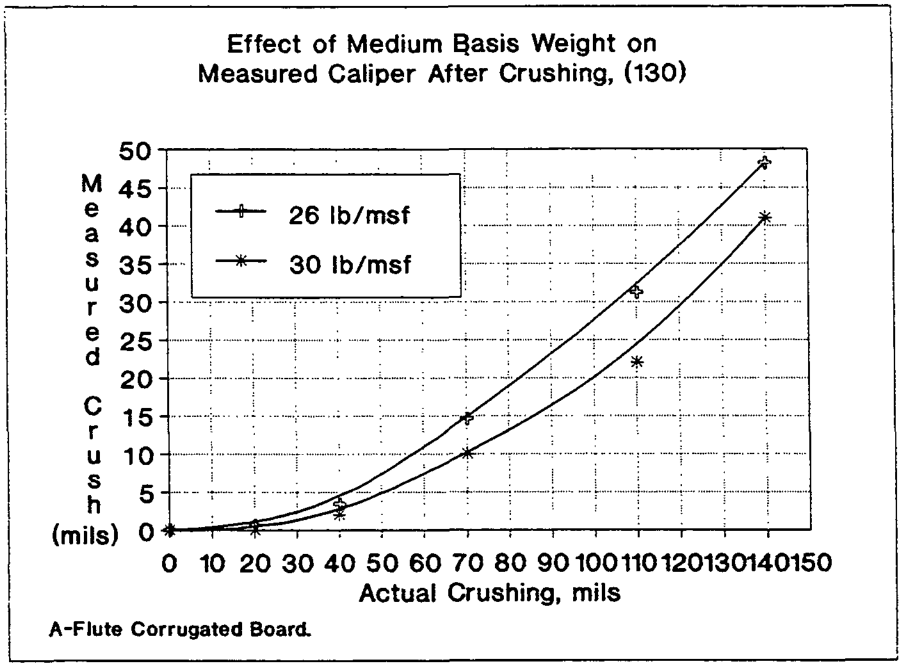
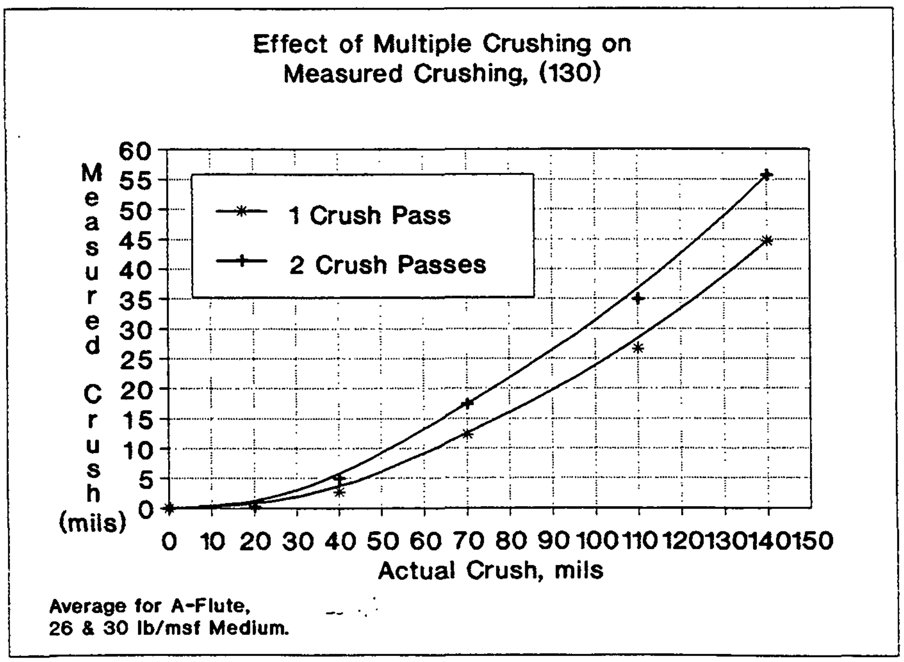


FIGURE 12.17
Effect of Combined Board Crushing on Postcrushing Combined Board Caliper





3. The flat crush strength of the combined board is influenced by the flute design of the corrugating rolls, by the physical properties of the corrugating medium, and by corrugating process variables.

4. Approximately 30% to 40% of the inherent flat crush strength of the medium is destroyed during the fluting process. Stronger or heavier basis weight mediums may or may not result in increased flat crush strength in the combined board. Most corrugating rolls are designed for 9-point, 26 lb/msf corrugating medium.

5. The major flute design variables affecting the resultant combined board flat crush strength include clearance allowances in the flute flank areas of the meshed corrugating rolls, the flute flank design angle, and the radius of curvature of the flute tips. Larger clearances and larger radii of curvature are favorable for flat crush strength retention. The flute flank angle is a complex issue.

6. For a given corrugating medium and a given fluting efficiency, B-flute has a higher flat crush strength than C-flute, and C-flute is stronger that A-flute. The differences are attributable to the effect of shorter flute sidewall height (less buckling) and the greater number of flutes per foot (more support) for B-flute over C-flute, and C-flute over A-flute.

7. A higher medium web temperature and moisture content reduce the flat crush strength loss during fluting. A 1 percentage point change in moisture content affects the flat crush strength by 2.8%, and a 20 deg.F. change in temperature affects the flat crush strength by 3.3%.

8. The flat crush strength retention during fluting is favorably affected by a higher medium density, a lower medium MD elastic modulus, and a higher ZD (thickness) elastic modulus. Added refining and wet pressing in the paper mill improves both the inherent, unfluted medium flat crush strength and the percent of flat crush strength retained in the combined board after fluting. The wet pressing effect is not as clear as the refining effect.

9. The Concora Test, while useful, is not consistent in accurately predicting the flat crush strength of the commercially fluted combined board. The Concora Test, while superficially similar to actual corrugating, does not include the factors of flute design, medium preconditioning, and fluting speed found in commercial operations. These factors have a large effect on damage caused by fluting.

10. Flute fracture adversely affects the flat crush strength.

11. Combined board caliper measurements in the box plant are a poor and insensitive method for judging the flat crush strength damage done by crushing of the corrugated board.

Chapter 13

Package Performance Issues

The corrugated packaging industry is thought, by some, to be a commodity-type business. Indeed, the linerboard and medium segment of the industry has engaged, for years, in material swap programs between companies in order to reduce freight costs. A swap program consists of the Company-A mill shipping rollstock to a nearby Company-B box plant rather than to a far away Company-A box plant, which is located near a Company-B mill. The Company-B mill then reciprocates by shipping an equal amount of rollstock to the Company-A box plant. Swapping was done under the assumption that all linerboard and all medium of a specified grade produced in the United States were equivalent, as long as they produced combined board that met the Item 222/Rule 41 specifications. Under the pre-1991 regulations, the specification parameters for linerboard included only mullen and basis weight, and for medium included only basis weight and caliper. "A 26 lb/msf medium was a 26 lb/msf medium, was a 26 lb/msf medium." This has changed. The industry is now looking very closely at the other quality attributes of the linerboard and medium, quality attributes which influence those functional performance properties of the corrugated package which are important to the package user.

The box plant segment of the industry has always been a job shop type of business. The boxes made for a given customer are unique to that customer. Indeed, the boxes are generally unique for each product line marketed by a given customer. The uniqueness can involve differences in the combined board construction, such as singlewall, doublewall, or triplewall; such as A-flute, C-flute, B-flute, E-flute, or F-flute; and/or such as the linerboard and medium grades. The differences can also involve other box attributes, such as box size and style; such as the use of nonskid, nonabrasive, or moisture barrier coatings; such as the print logo; and/or such as the unitizing pattern.

This publication deals with the subject of corrugating medium and its influence on box plant operations, combined board properties, and package performance. The effect of the medium on package performance requires an analysis of the functional requirements of corrugated packaging and the role, if any, that the medium plays in meeting each of the requirements.

Figure 13.1 lists the seven major corrugated box performance criteria considered critical by box customers. The seven criteria are: to contain the product, to protect the product, to stack the product, to advertise the product, to operate reliably on high-speed packing lines, to meet regulatory requirements, and to meet any individual customer specifications agreed upon. These seven major criteria may vary in importance depending on the individual packaging application; however, they are equally important in terms of the overall corrugated packaging business.

There are four mechanisms by which the box can fail to contain the product. First, the manufacturer's joint can open. The failure can occur in the linerboard-to-linerboard glue joint made when the box was folded and glued. This failure mode does not directly involve the corrugating medium. The failure can occur in the corrugator bond between the linerboard and the medium. The influence of the corrugating medium on this type of failure mode is discussed in Chapters 6, 7, and 8.

Second, the flaps of the sealed and filled box can open. This type of failure involves the linerboard and adhesive application. It does not involve the medium.

Third, the box scorelines can separate. Research work done at the Institute of Paper Science and Technology has shown that scoreline separation failure is initiated when the stress on the scoreline exceeds the tensile energy absorption (TEA) of the combined board at the scoreline. Once the failure has been initiated, further propagation of the scoreline separation is governed by the tear strength of the corrugated board at the scoreline. The corrugating medium will contribute to the TEA of the combined board in the flap score areas but not in the body score areas. It does not contribute to the body score TEA since the flute structure will expand like an accordion, and the tensile force will be applied only to the linerboard components. The medium will contribute to the tear resistance of both the flap and body scorelines

FIGURE 13.1

Major Corrugated Box Performance Criteria

- ★ Contain the Product.
- ★ Protect the Product.
- ★ Stack the Product.
- ★ Advertise the Product.
- ★ Perform on High-speed Packing Lines.
- ★ Meet Regulatory Requirements.
- ★ Meet Customer Specifications.

and, therefore, influence the severity of the scoreline separation.

Fourth, the corrugated board can be punctured. The corrugating medium adds directly to the puncture resistance of the combined board. The puncture of the corrugated board will increase directly with the increasing tear strength of the medium and with the increasing height of the flute. For a constant linerboard and medium material, the puncture energy will be the highest for A-flute and followed in decreasing energy by C-flute, B-flute, E-flute, and F-flute.

The protection of the packaged product is influenced by the cushioning characteristics of the combined board. The ability of corrugated board to absorb and dissipate shock impact forces is governed by the flat crush characteristics of the fluted medium. The influence of the corrugating medium on the combined board flat crush is discussed in Chapter 12.

The stacking strength of a corrugated box is determined by many factors, including those related to material strength, package design, and field use conditions. The scope of this publication is limited to the material strength factors influenced by the corrugating medium. The box compressive strength model developed by Robert McKee and published in 1963 shows that the top-to-bottom compressive strength of RSC-style boxes is determined by the CD Edge Crush Test (ECT) and the MD and CD Flexural Stiffness of the corrugated board used to manufacture the box.

The corrugated medium contributes directly to the combined board CD ECT. The CD ECT is proportional to the sum of the CD edge crush strength (Ring Crush or STFI Crush) of the linerboard and medium materials used to manufacture the corrugated board. The effect of the medium on CD ECT is discussed in Chapter 11.

The flexural stiffness of the combined board is equal to the sum of the stiffness contribution (Elastic Modulus times Moment of Inertia) of the various linerboard and medium components. This assumes that the corrugated board acts as a unified, sandwich- type structure. The corrugating medium serves to bridge and bond the linerboard plies together to form the unified structure. The effect of the medium on the strength of its bonding to the linerboard is discussed in Chapters 7 and 8.

The direct stiffness contribution of the medium to the total combined board stiffness is relatively small as compared to the contribution of the linerboard. In fact, the medium does not contribute to the MD Flexural Stiffness Test because of the ability of the flute structure to flex in this direction. The medium does contribute to the CD Flexural Stiffness Test. However, the medium contribution is relatively small because of its small Moment of Inertia, being located in the center portion of the sandwich structure. The medium contributes only between 5% and 10% to the total Flexural Stiffness Test in singlewall board. The effect of the corrugating medium on the combined board flexural stiffness is discussed in more detail in Chapter 10.

The medium does not influence the ability of the box to effectively advertise the product. The printing is done on the linerboard surface. The flute size does have some effect on the print quality. The linerboard, particularly a low basis weight linerboard facing, can deflect in the areas located between the flute tips (washboarding) and produce an uneven surface for printing. The tendency to washboard is reduced as the spacing between the flute tips decreases. F-flute would be expected to have the most even surface, and A-flute would be expected to have the most uneven surface.

Assuming proper box dimensions and proper vacuum systems on the box setup machine, the most important factors affecting the performance of boxes on high-speed packing are the flatness (lack of warp), stiffness (rigidity) of the corrugated board, and well- defined scorelines. The medium has very little effect on warp and should provide sufficient rigidity to the board, provided that there are no blatant quality problems, such as fractured flutes or unbonded areas between the linerboard and medium (blisters or loose liner defects).

The medium can influence the ability of the box to comply with various regulatory requirements. Specifications dealing with compressive strength and drop testing are particularly influenced by the corrugating medium. The different regulations (Item 222, Rule 41, DOT, FDA, USDA, Military, United Nations, etc.) have specification requirements that are too complex and varied to discuss in detail in this publication. This is also true of the individual customer specifications. The reader will have to seek this information elsewhere.

In summary, the major box performance criteria most strongly influenced by the corrugating medium are "Stack the Product," "Contain the Product," and "Protect the Product." These three areas are discussed in more detail in Chapters 14 and 15.

It is important to keep in mind that the relationships between medium properties and combined board properties described in Chapters 14 and 15 are based on having good box plant fabrication and converting quality. The results shown are not influenced by the obvious fabrication and converting defects, such as high/low flutes, fractured flutes, leaning flutes, poor corrugator bond strength, poor scoring, excessive crushing, or out-of-square boxes. The effects of these process defects were discussed in prior chapters.

Chapter 14

Package Compressive Strength

The performance standard for corrugated paperboard packaging is generally based on compressive strength and the ability of the package to retain its strength and rigidity under humid conditions. The stacking capability is the major characteristic that differentiates a corrugated box from a paper bag, a plastic bag, a paper wrap, a plastic wrap, or any other type of flexible package. Box compression strength is more relevant today because of the changes that have occurred in the handling and warehousing of packaged goods. Rule 41 and Item 222 were changed in 1991 to recognize an alternate, compressive strength-based specification for defining acceptable corrugated packaging. Box compression, in conjunction with flat crush strength and puncture resistance, is also a good indicator of the rough handling endurance of the package, (2, 123).

The paper industry is continuing to move in the direction of using heavily loaded or long nip wet presses on paper machines to improve the strength levels obtained from each pound of paper fiber. The industry is reducing the weight of packaging and eliminating overpackaging. Corrugated packaging is now more consistent in compressive strength performance. The corrugating medium plays several key rolls in determining the compressive strength performance of boxes. It adds directly to the edge compressive strength of the corrugated board. It contributes marginally to the bending stiffness of the combined board. It is the one and only component that can keep the linerboard facings separated for stiffness and yet bound together to form a unified structure, all at the same time, (9, 24).

Figure 14.1 shows a mathematical model for predicting the top-to-bottom compressive strength of RSC-style corrugated boxes. It was published by Mr. Robert McKee in 1963. The model shows that the box compressive strength is determined by the size of the box (as indicated by the box perimeter), by the pure compressive strength of the combined board (as indicated by the CD Edge Crush Test), and by the elastic buckling resistance of the corrugated board (as indicated by the combined MD and CD Flexural Stiffness). Box compression failure lies between the pure compression and the elastic buckling physical performance regions of the corrugated board, (36, 37, 44, 55, 123).

Figure 14.2 shows a similar mathematical model for predicting the end-to-end compressive strength of a corrugated box. This style of box is typically used when unit loads of filled boxes are handled during transportation and warehousing with trucks equipped with side-to-side clamping devices. In an end-to-end compression design box, the outer flaps are the main contributors to the total box compressive strength. Compression failure generally initiates in the outer flaps, in the area located between the inner flaps. The box length, width, and depth appear in this equation. The top-to-bottom compression model includes only the length and width. The corrugated board strength factors included in the model are the combined MD and CD flexural stiffness and the MD Edge Crush Test. The MD edge crush strength is determined only by the edge crush strength of the linerboard facings. The medium does not directly contribute to MD ECT as it does to CD ECT. However, the medium does, in MD ECT, act to reinforce the linerboard at the bond sites and to act as a bridge between the linerboard facings so that they act as a unified structure. The reported average absolute error of the estimate for the end-to-end box compression model is 8.2%, as compared to the reported top-to-bottom compression model average absolute error of 6.1%, (141).

The effect of the corrugating medium basis weight on the top-to-bottom compressive strength of corrugated tubes is shown in ***Figure 14.3***. The tubes were produced on a pilot-size corrugator using commercially produced linerboard and medium. The effect of medium basis weight and flute size on the top-to-bottom and end-to-end compressive strength of boxes is shown in ***Figure 14.4***. The boxes were produced in a commercial box plant operation using commercially produced linerboard and medium, (73, 82, 99).

All three plots show that the effect of the medium basis weight on package compression strength is not linear. The data indicate that increasing the medium basis

FIGURE 14.1
Top-To-Bottom Box Compression Equation

$$P = 2.028\,(P_m)^{0.746}\,\left[(Dx)(Dy)\right]^{0.127}\,(Z)^{0.492}$$

P = Box Compression Strength, lb.

P_m = Corrugated Board CD Edge Crush Test, lb/inch.

Dx = Corrugated Board MD Flexural Stiffness, lb-inch.

Dy = Corrugated Board CD Flexural Stiffness, lb-inch.

Z = Box Perimeter, inch.

R. McKee, Paperboard Packaging, August 1963

FIGURE 14.2

End-To-End Box Compression Equation, (141)

$$P = 0.15\,(Pmx)(2d) + 3.10(Pmx)^{0.787}\left[(Dx)(Dy)\right]^{0.106}\left(1 + \frac{W}{L}\right)^{0.512}(W)^{0.574}$$

P = Box Compressive Strength, lb.
Pmx = MD Edge Crush Test, lb/inch.
d = Box Depth, inch.
Dx = MD Flexural Stiffness, lb-inch.
Dy = CD Flexural Stiffness, lb-inch.
W = Box Width, inch.
L = Box Length, inch.

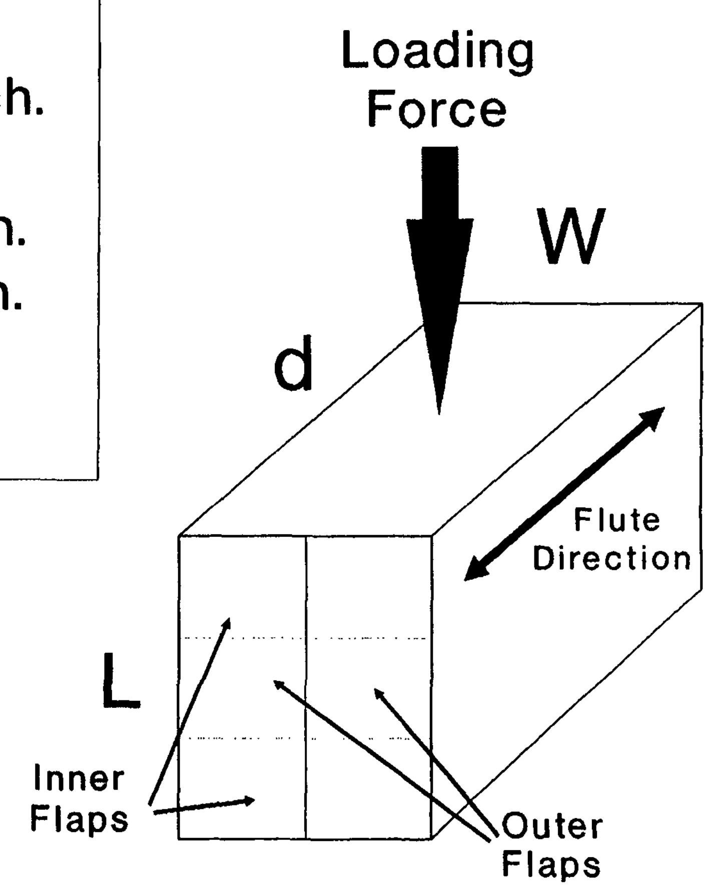


FIGURE 14.3

Effect of Medium Basis Weight on the Top-To-Bottom Tube Compressive Strength, (99)

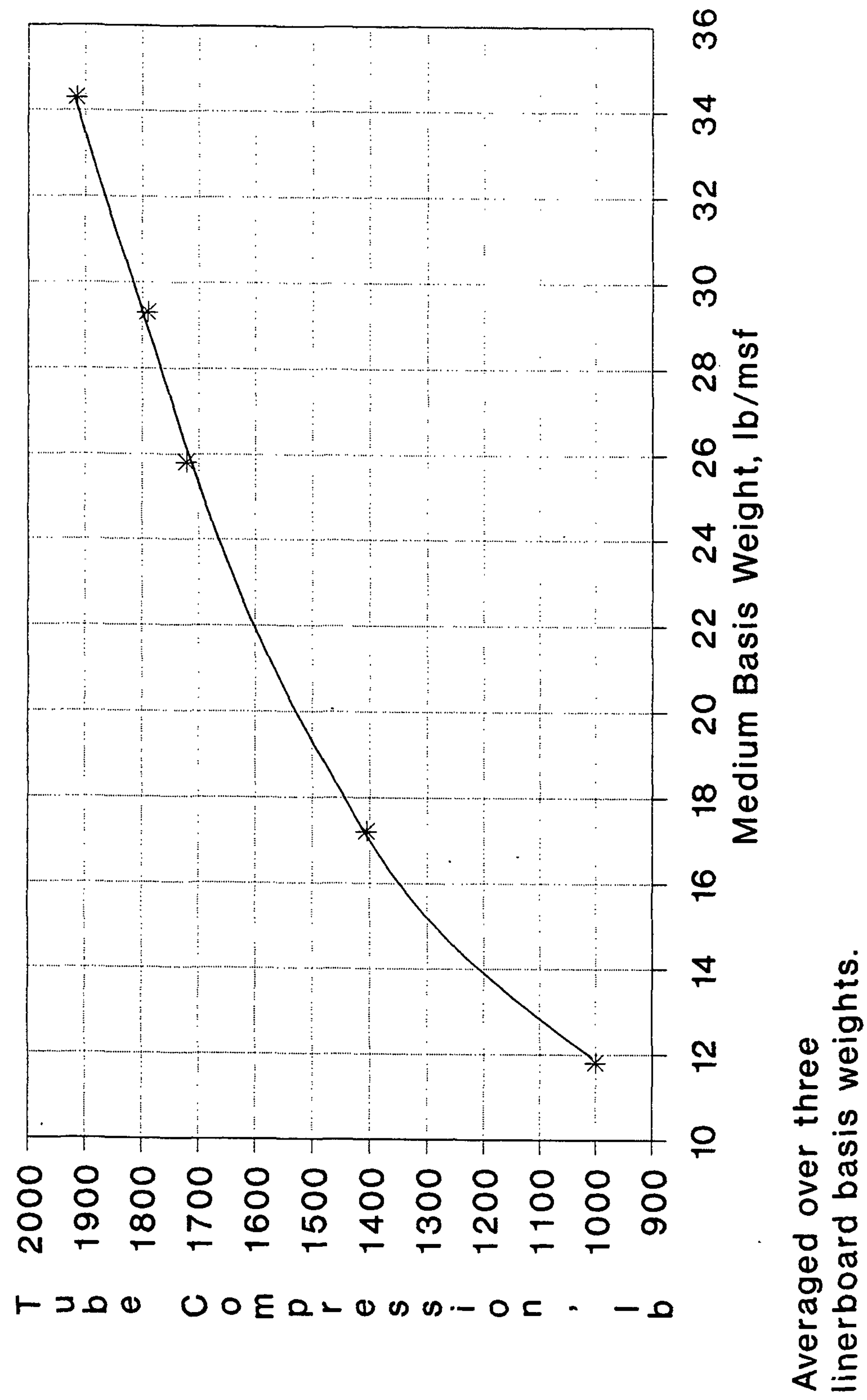
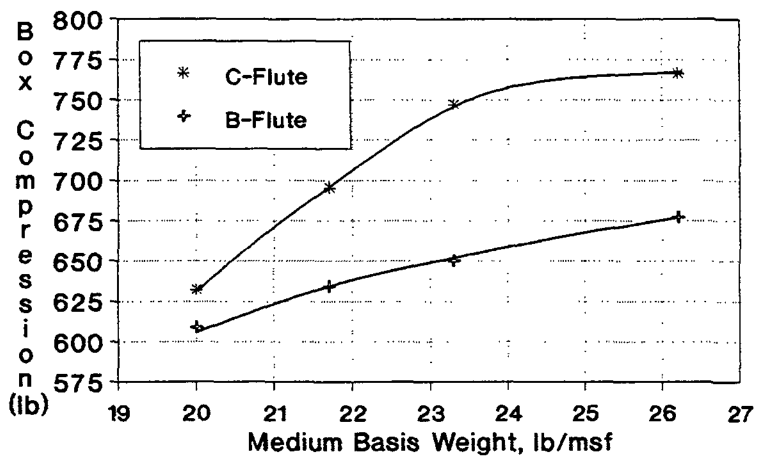


FIGURE 14.4

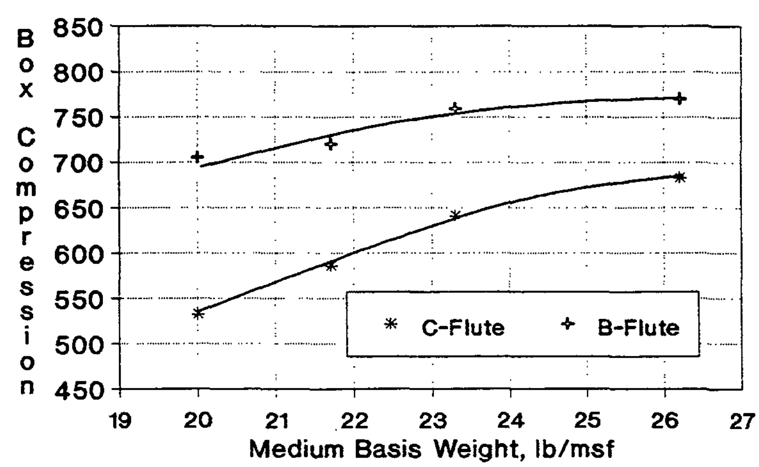
Effect of Medium Basis Weight on Top-To-Bottom and End-To-End RSC Box Compressive Strength

Effect of Medium Basis Weight on
Top-To-Bottom RSC Box Compression, (82)



42 lb/msf Linerboard Facings.
Average of Two Box Sizes.

Effect of Medium Basis Weight on
End-To-End RSC Box Compression, (82)



42 lb/msf Linerboard Facings.
Average of Two Box Sizes.

weight has a diminishing benefit on the observed package compressive strength. This observation can be attributed to the fact that the medium contributes little to the combined board flexural stiffness strength term in the models. It may also be attributed, in part, to the fact that the higher basis weight medium may be damaged more by the fluting process. Most corrugating rolls are designed to operate most effectively with 26 lb/msf, 9-point medium material, (32, 34, 130).

It should be noted that C-flute board yields a higher top-to-bottom compressive strength box than B-flute board, all other material and quality factors being equal. However, the opposite is true for the end-to-end compression where B-flute boxes are stronger than C-flute boxes. In both cases, the C-flute board has a higher flexural stiffness than the B-flute board, and a higher flexural stiffness will increase the box compressive strength, as shown by the equations in ***Figures 14.1 and 14.2***. However, the flute size has little effect on the CD edge crush strength of the combined board, but the flute size has a large effect on the MD edge crush strength. With MD ECT, the closer flute spacing in the B-flute board serves to better reinforce the compression resistance of the linerboard facings.

The MD ECT test specimen can be envisioned as a series of tiny linerboard plate segments piled one on top of another. The top and bottom of each "plate" are represented by the corrugator bond gluelines. The shorter height "plates" that result from the closer flute spacing with B-flute increase the reinforcement of the linerboard facings against buckling between the flute tips. This added reinforcement produces a higher maximum edge crush strength. The edge crush strength has a much greater relative effect on box compression than does the flexural stiffness strength, (73, 82, 99), and this causes the B-flute boxes to be stronger in end-to-end compression than C-flute boxes of the same size, material, and quality. Similarly, C-flute boxes are stronger than A-flute boxes in end-to-end compression.

Because of these effects, the medium basis weight (can be interpreted as strength) affects the end-to-end box compression slightly more than the top-to-bottom box compression. This experimental observation is demonstrated in ***Figure 14.5*** where the change in end-to-end box compression due to changes in the medium basis weight is plotted against that for the respective top-to-bottom compression. The slope of the regression lines for both the B-flute and C-flute constructions documents a greater rate of compression change with medium basis weight for the end-to-end compression-style package, (82).

Figure 14.6 shows the results of another experiment to determine the effect of medium basis weight on box compressive strength. The data indicate that a 61% increase in medium basis weight (strength) produces a top-to-bottom box compression increase of 29%. The total fiber usage, linerboard and medium, increased by only 17%. The data are based on commercially produced boxes, (36).

A corrugated box is a complex structure to which the traditional engineering concepts of stress, strain, equilibrium, and compatibility can be applied. The engineering objective is to have all of the components act as a unified structure and to have each component reach its maximum load bearing capability at the same time so that the total structure failure occurs at the highest possible loading, (50, 52, 53, 58). The top-to-bottom compression force on a RSC-style box must be supported by the four vertical panels of the box. The load causes the panels to buckle and bend in the center while the corners of the box, formed by the junction of two panels, remain vertical. As the compression load increases, the vertical edges of the panels must support a higher percentage of the total load on the box.

Assuming that the box side panels bulge outward, the inner linerboard experiences a compression force, and the outer linerboard facing experiences a tensile force. The maximum compression stress (load) occurs in the inner linerboard facing at the side panel corners formed by the two panels and the box flaps. The maximum tensile stress occurs in the outer linerboard facing at the side panel corners formed by the two panels and the box flaps. The linerboard compression strain (deflection) at failure is less than the linerboard tensile strain at failure. Actual box compression failure, therefore, initiates in the inner linerboard facing at the corner of the side panel, assuming no major quality problems, such as a blisters, exist. The typical bowed failure lines seen on the outside of the box are actually post-compression failure symptoms. This primary box compression failure mode is also true for internal forces exerted on the panels of a box by a flowable product, such as resin pellets or a liquid, that is packed inside the box, (52, 53, 58).

This failure mode is demonstrated in ***Figure 14.7*** where the top-to-bottom compression failure load for two unbalanced linerboard constructions is compared. The 42-26-69 lb/msf C-flute combined board had, on average, a 31% higher compressive strength than the 69-26-42 lb/msf C-flute construction, (52, 53, 58).

The application of engineering approaches to corrugated paperboard packaging raises the question about the balance in properties and/or basis weight between the linerboard facings and the medium. ***Figure 14.8*** shows one approach to handling this linerboard/medium balance issue for singlewall corrugated board boxes. It is presented only as an example of the concept of material balance. This author does not take a position as to the validity of the conclusions based on this particular computer model.

The researcher used the box compression model

FIGURE 14.5

Relative Effect of Medium Basis Weight on T/B and E/E Box Compressive Strength, (82)

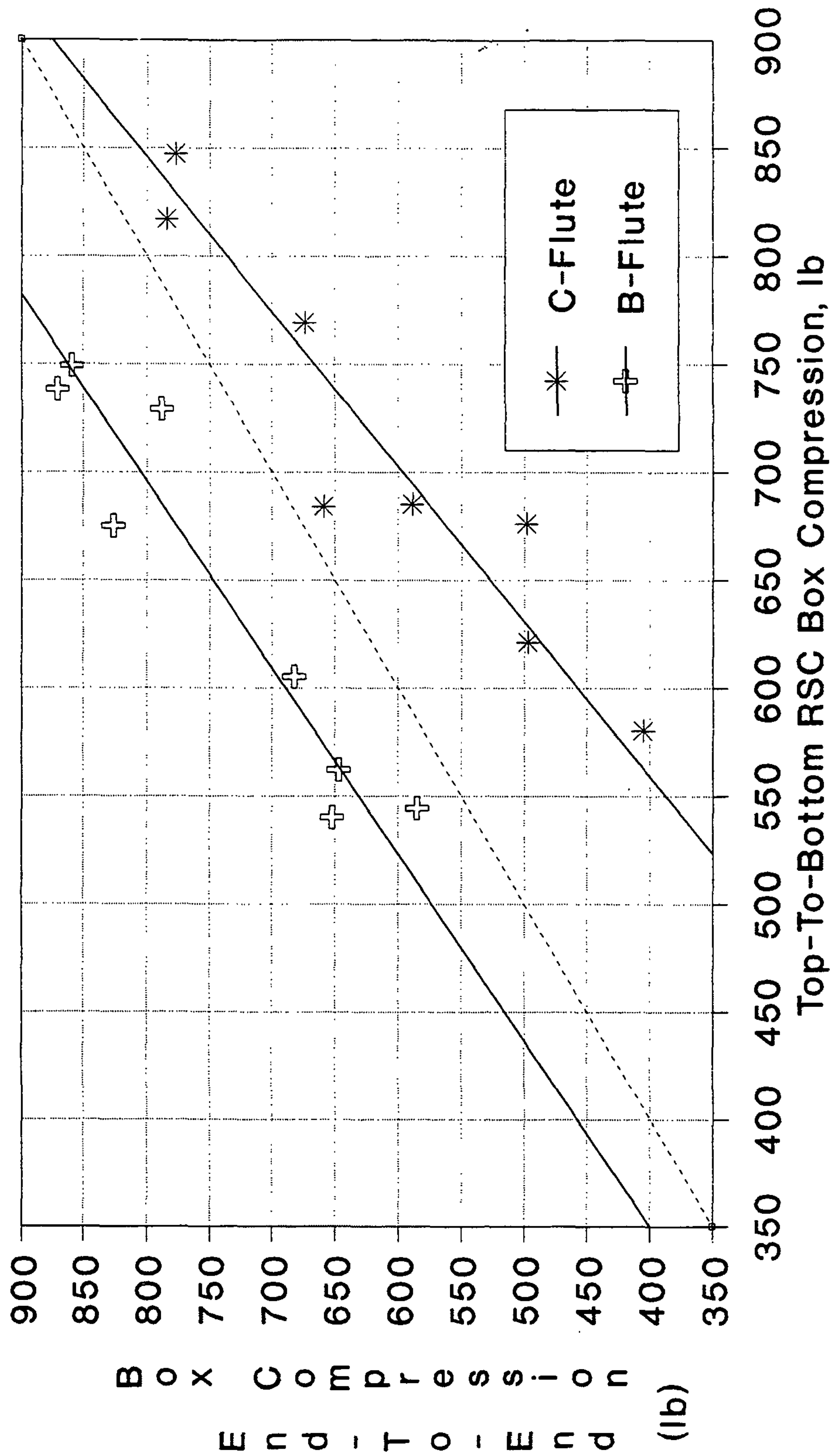


FIGURE 14.6
Effect of Medium Basis Weight on
Box Compressive Strength, (36)

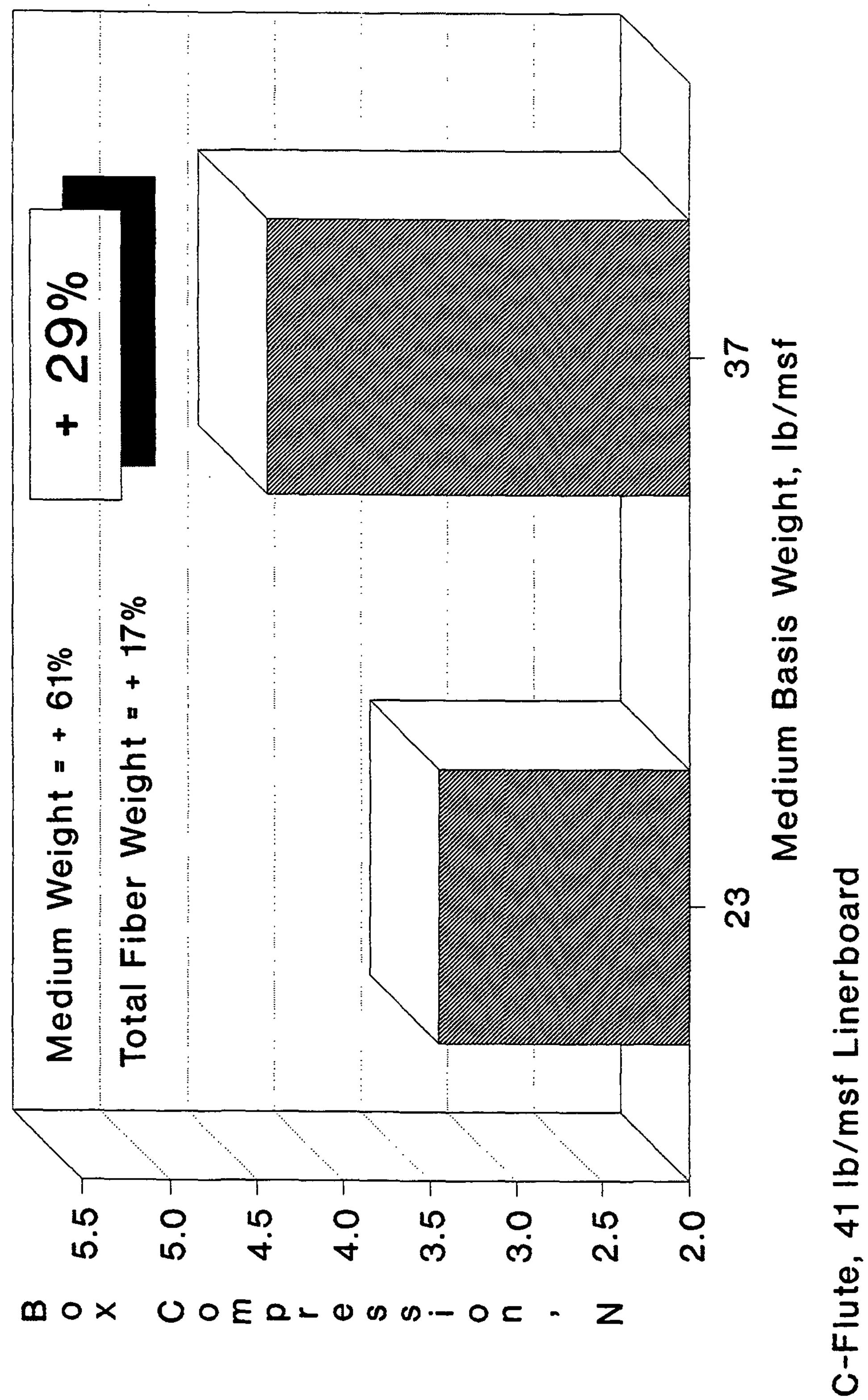


FIGURE 14.7

Effect of Inner Linerboard Basis Weight on Top-To-Bottom Compressive Strength of a Corrugated Box Panel, (52, 53, 58)

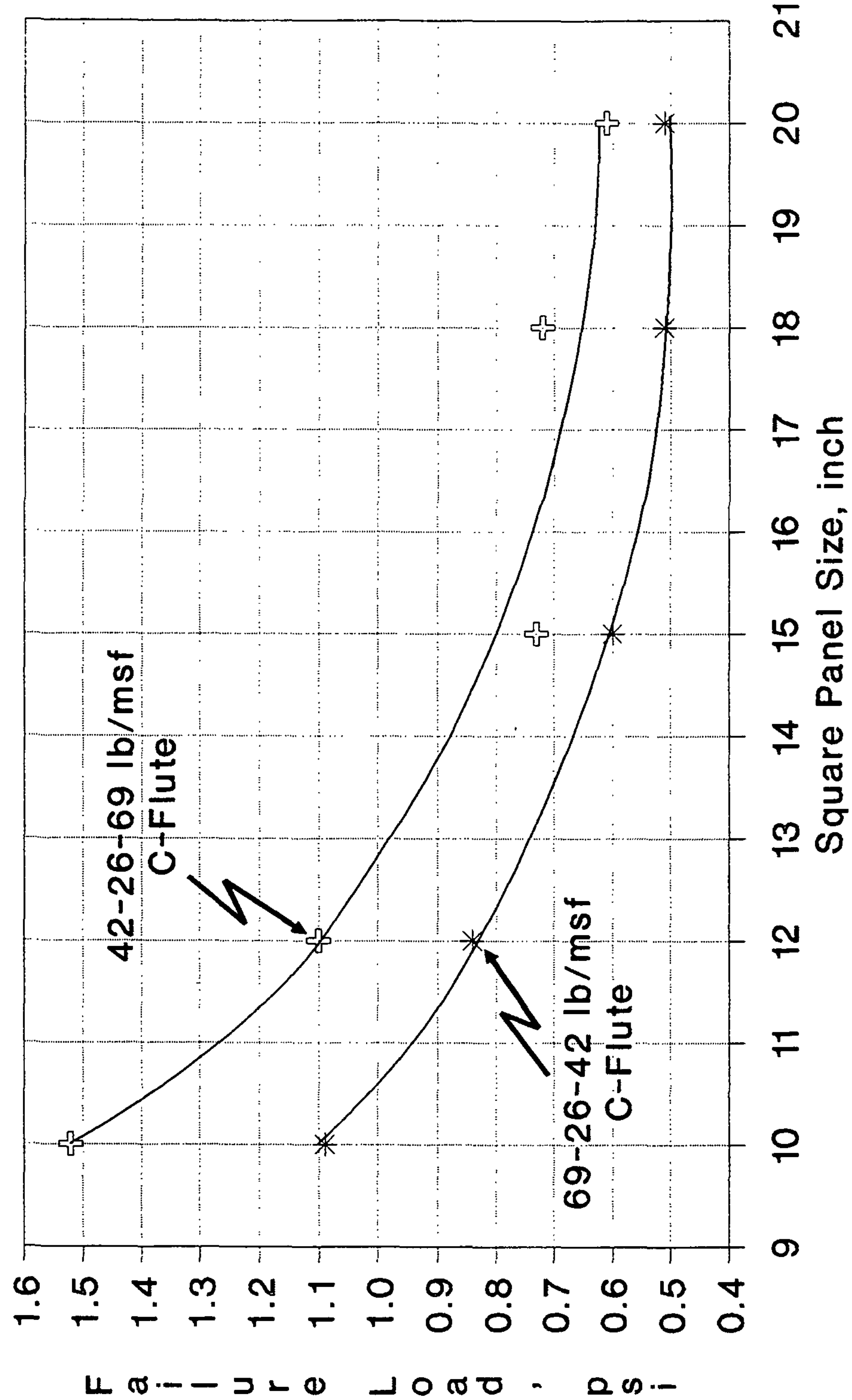
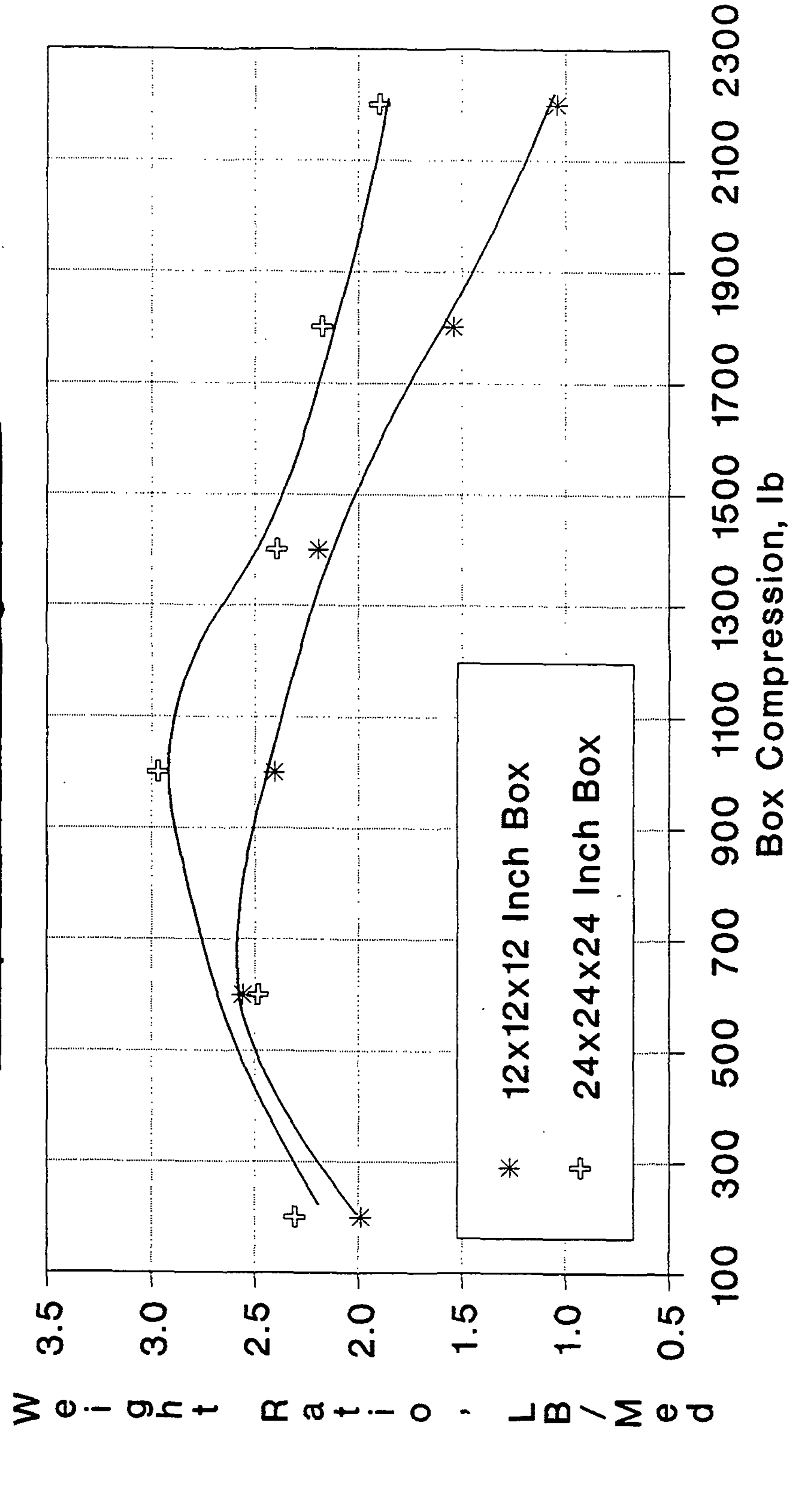


FIGURE 14.8

Balance of Linerboard and Medium to Achieve Minimum Fiber Box Compressive Strength, (55)



A-Flute Boxes. Computer Model Results.
Weight Ratio Based On Two Liners And
1.55 Medium Draw Factor.

shown in ***Figure 14.1***, and assumed a continuous basis weight grade structure for both the linerboard and medium. A higher ratio value in ***Figure 14.8*** denotes relatively more linerboard usage and relatively less medium usage. The traditional 42-26-42 lb/msf C-flute corrugated board grade has a ratio of 2.24; the 69-26-69 lb/msf C-flute grade has a 3.68 ratio; and the 33-26-33 lb/msf C-flute grade has a ratio of 1.76. The calculations are based on achieving the defined box compressive strength at the lowest fiber cost. The calculations indicate that a larger box should have a higher ratio value (more linerboard, less medium). This result can be attributed to the significant effect of the linerboard on the flexural stiffness term of the box compression equation model. The calculations for both size boxes show a maximum ratio in the mid-compressive strength range, and a decreasing ratio particularly on the higher compressive strength side of the range. This indicates that higher compressive strength requirements for a given size box should consider increasing the medium basis weight proportionately more than the linerboard basis weight, (36, 50, 55, 64, 99).

The literature contains many other approaches (computer models) that address this balancing act. They are not included in this reference publication since it would be impossible to judge their relative merits. This author will just repeat the familiar warning given for all computer model applications, "Garbage In = Garbage Out!"

Figure 14.9 shows the effect of corrugator bond glue skips on the top-to-bottom compressive strength of boxes. The corrugated board was produced on a pilot-size corrugator using commercially produced linerboard and medium. The adhesive gaps were produced by using a wiper blade on the applicator roll. The gap, therefore, ran around the complete perimeter of the box. The data show no effect on the box compression until the gap was approximately 1/3 inch wide. A 1/2 inch gap reduced the box compression by 11%, and a 1 inch gap reduced the box compression by 27%, (116). While the experiment was conducted by removing a strip of adhesive, similar results would be expected for MD- oriented corrugator blisters. This author wishes to point out that these results are based on the standard laboratory box compression test procedure. This author expects that the effect of bond gaps on the actual stacking performance of the box in the field will be much worse than that indicated by these laboratory test data.

This issue of the translation of laboratory test results into the expected field performance of corrugated boxes should always be of top concern to packaging engineers and package producers. An example, often used by this author to make the point, is the placement of a 2-by-4 wooden stud in the center of a corrugated box. The laboratory compression test will show unbelievably high strength levels. The box will be a disaster in the warehouse. There are no easy answers to this knotty translation problem that this author can offer, except for experience and caution. The laboratory is not the "real world;" it is just a powerful tool for trying to deal with the complexities of real life.

The effect of the crushing of the flutes in the side panels of the box on box compression strength is shown in ***Figure 14.10***. The ratio of the corrugated board flat crush strength divided by the crushing force is shown plotted against the box compressive strength expressed as a percent of that of the uncrushed box. A low ratio value represents worse crushing. The boxes were produced in a commercial box plant. The data show that the end-to-end box compressive strength is less sensitive to low levels of crushing force than is the top-to-bottom box compression. The top-to-bottom strength is affected almost immediately, even at a flat crush force ratio of 4.0 to 4.5. The end-to-end box compression strength was not affected until the ratio decreased to 3.0. However, once the end-to-end compressive strength started to be affected, it dropped at a faster rate than that of the top-to-bottom. This difference in rate of compression loss is shown in ***Figure 14.11***, (73).

The effect of the water resistant corrugator adhesive on box compressive strength at various relative humidity levels is shown in ***Figure 14.12***. The test boxes were 20.5 x 13.5 x 12.5 inch in size and were manufactured in a commercial box plant. The data show no detectable effect of the water resistant adhesive under the standard laboratory box compressive testing methods. ***Figure 14.13*** shows the stack life creep failure tests for the same boxes. This creep failure test more closely represents the field stacking conditions existing during warehouse storage periods. That is, the boxes are evaluated for compression performance while under load for an extended time period. The creep failure data show that the use of the water resistant corrugating adhesive greatly reduced the rate at which the boxes failed under stack loading conditions. The magnitude of the box performance improvement increases with increasing box moisture content. The water resistant adhesive improved the stacking life by 6% at a box moisture content of 7.5% (approximate TAPPI standard conditioning), and by 12% at a box moisture content of 12.5%. Similar experiments were conducted to evaluate the effect of wet strength grades of linerboard and medium. The use of wet strength components did not significantly affect either the laboratory compression test strength or the compression creep failure rate, (7, 87).

In summary, the technical information presented in this chapter supports the following observations concerning box compressive strength.

1. The stacking capability is the major characteristic that differentiates a corrugated box from a paper

FIGURE 14.9
Effect of Corrugator Bond Gaps on
Top-To-Bottom Box Compression. (116)

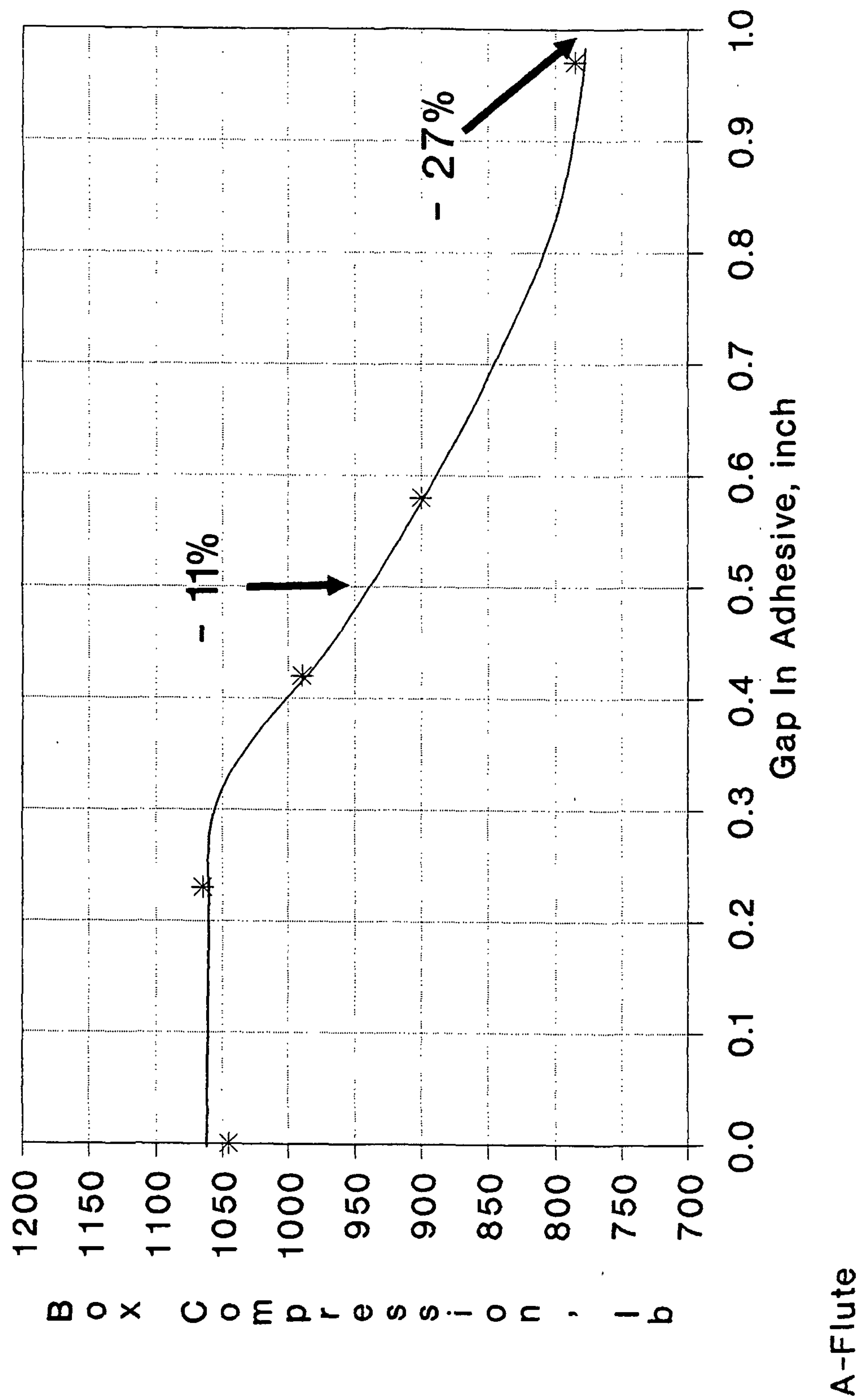
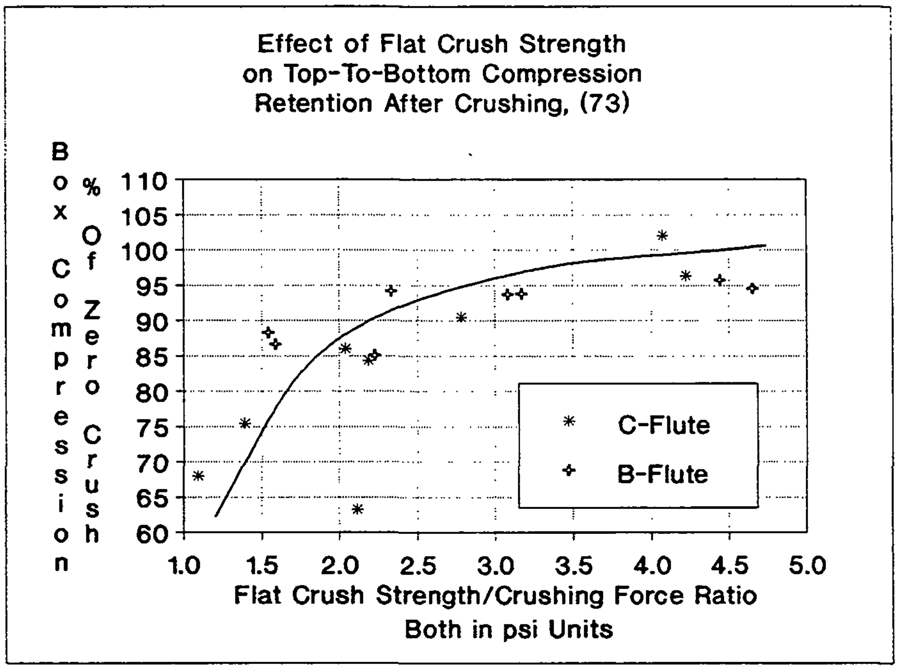


FIGURE 14.10
Effect of Box Panel Crushing on Box Compressive Strength



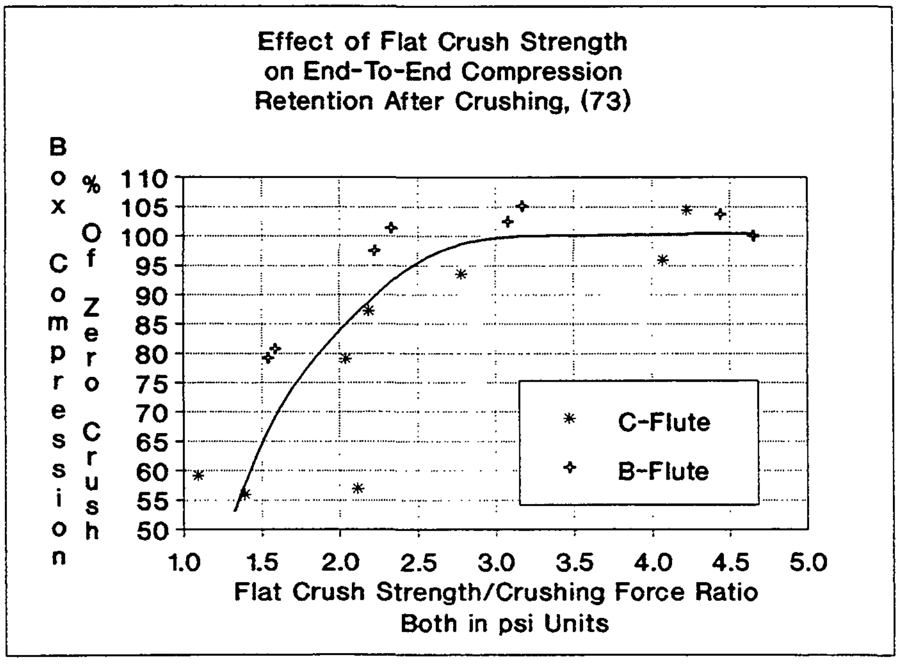


FIGURE 14.11
Relative Effect of Panel Crushing on Box Compression - T/B Versus E/E, (73)

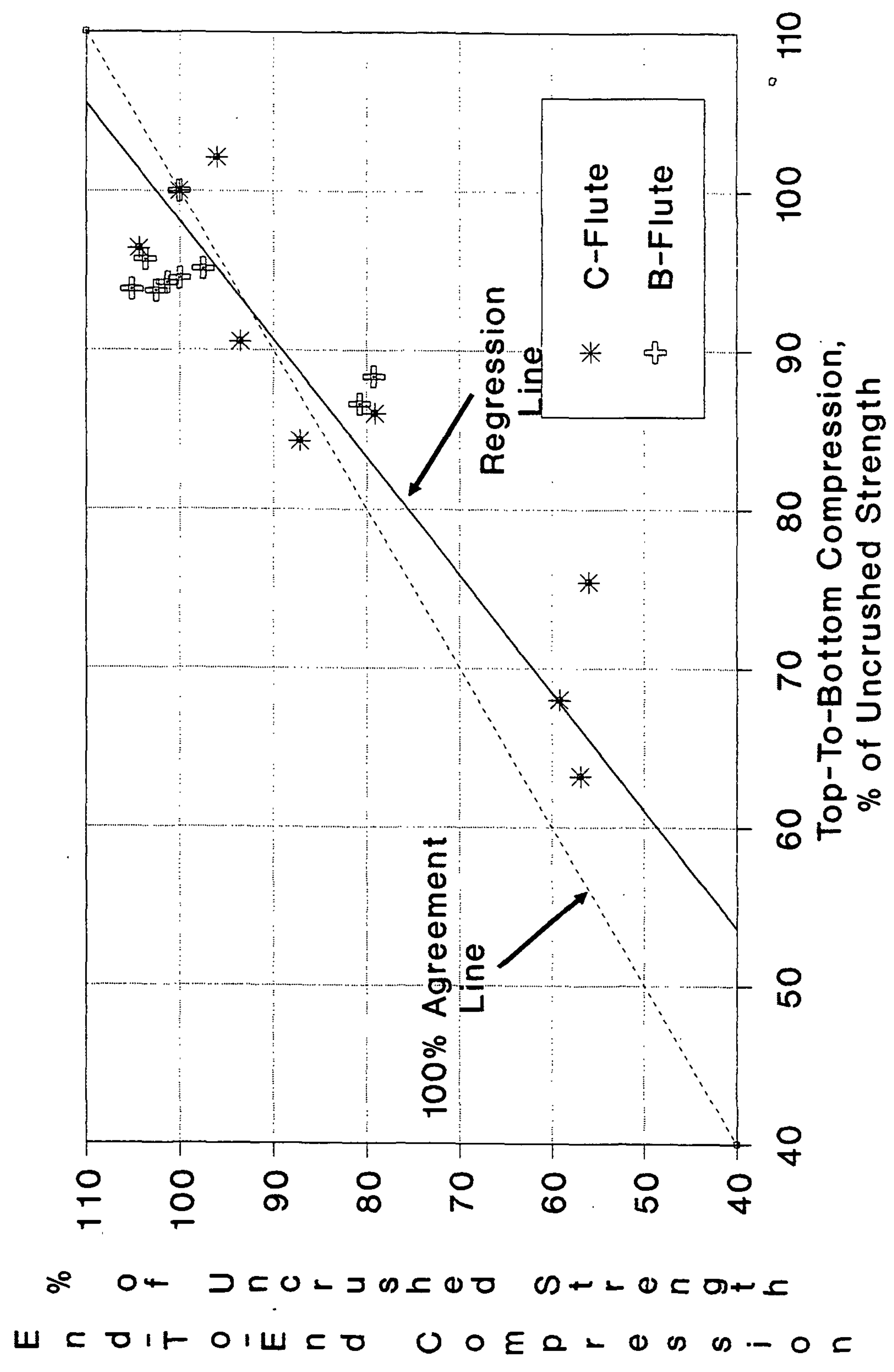
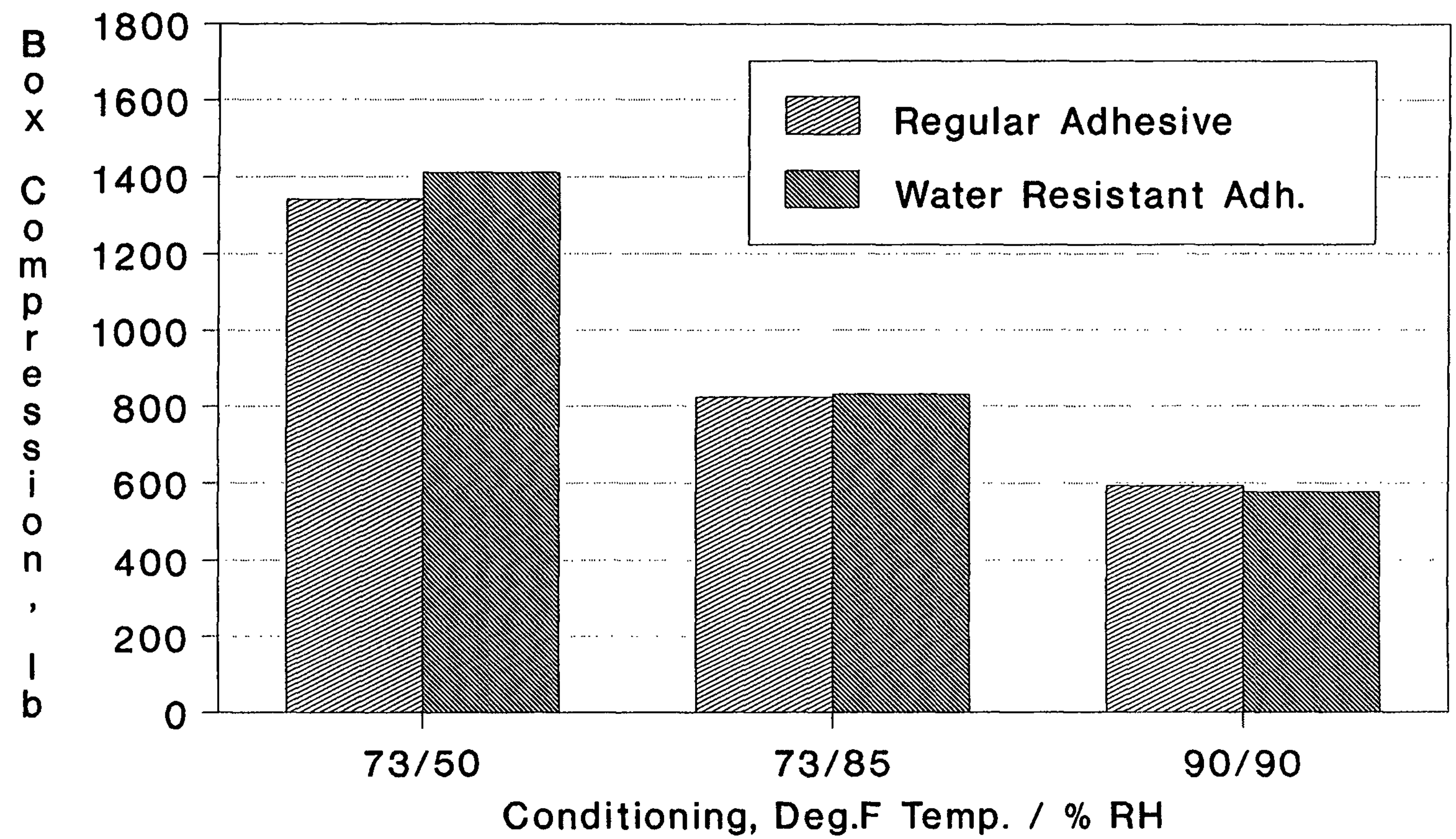
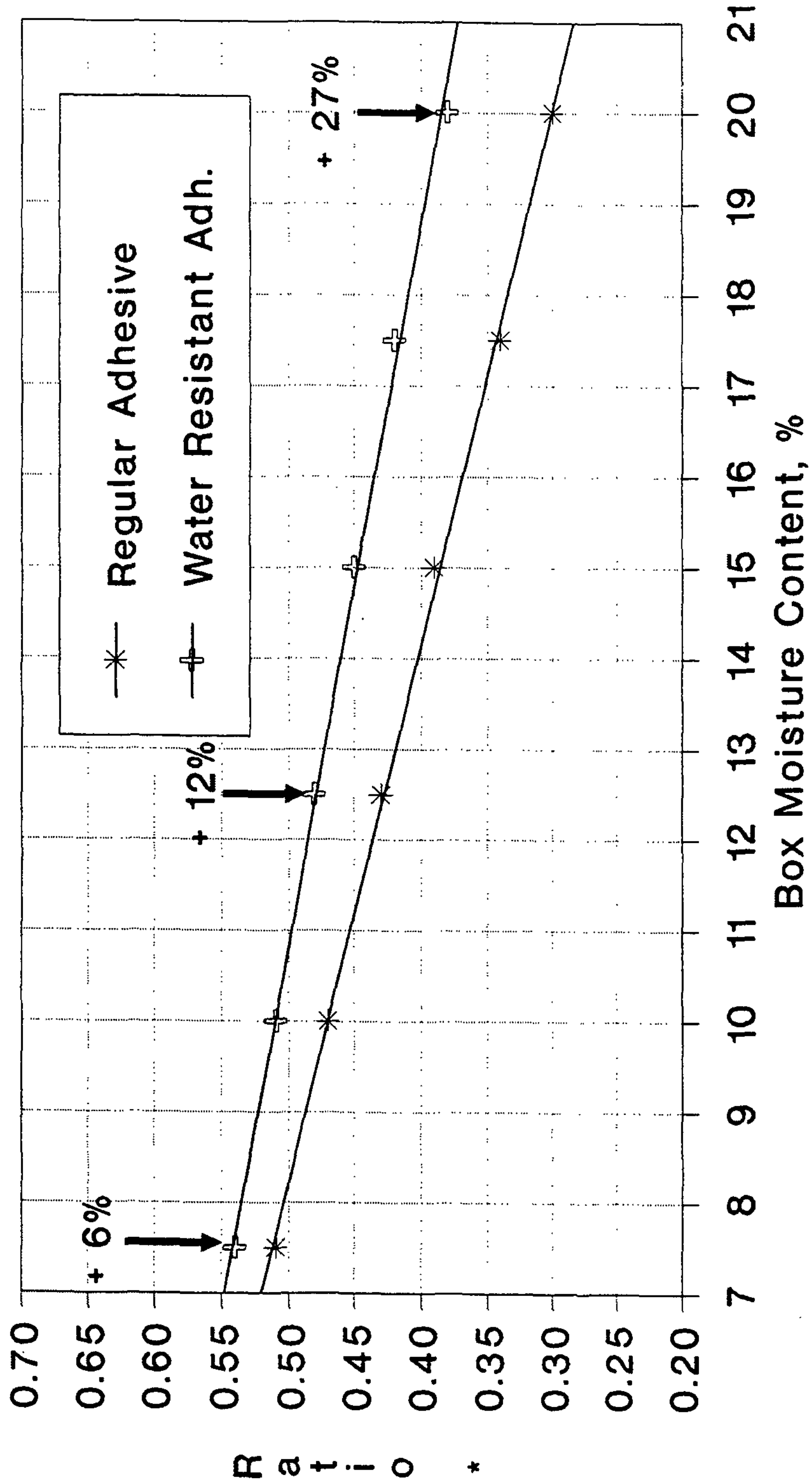


FIGURE 14.12
Effect of Water Resistant Corrugator Adhesive on Box Compression, (87)



90-26-90 lb/msf Construction,
C-Flute Boxes

FIGURE 14.13
Effect of Water Resistant Adhesive on Box Stacking Life Creep Failure. (87)



* Ratio is applied stack load divided by the box compressive strength at the moisture content shown.

bag, a plastic bag, a paper wrap, a plastic wrap, or any other type of flexible package.

2. Mathematical models are available for predicting the top-to-bottom and end-to-end compressive strength of boxes. Both models incorporate various forms of the box size, the pure compressive strength of the corrugated board, and the elastic bending resistance of the combined board.

3. The effect of the medium basis weight on package compression strength is not linear. The data indicate that increasing the medium basis weight has a diminishing benefit on the observed package compressive strength. This observation can be attributed to the fact that the medium contributes little to the combined board flexural stiffness strength.

4. Assuming all material and other quality issues remain constant, A-flute board produces a higher top-to-bottom box compressive strength than C-flute board, and C-flute board boxes are stronger in compression strength than B-flute boxes. The flute size effect can be attributed to the influence of the corrugated board thickness on the flexural stiffness strength.

5. The opposite is true for end-to-end box compressive strength. B-flute boxes are stronger than C-flute boxes, and C-flute boxes are stronger than A-flute boxes. This flute size effect can be attributed to the large effect that the closer flute spacing has on the MD Edge Crush Test strength of the combined board. The ECT effect overshadows the flexural stiffness effect.

6. Assuming that the box panels bulge outward under compression loading, box compression failure is initiated by compression failure of the inner linerboard facing near a corner of the panel. The typical bowed failure lines seen on the outside of the box that has failed in compression follow the maximum stress lines but are actually postcompression failure symptoms. Box compression strength can be improved by placing the strongest linerboard facing on the inside of the box, all other things being equal.

7. The crushing of the flutes in the side panels of the box has a large detrimental effect on box compression. The effect is proportionately greater than that indicated by box plant caliper measurements on the combined board.

8. The use of the water resistant corrugator adhesive has little effect on the box compressive strength as measured with a standard laboratory compression tester, even under high humidity conditions. The water resistant adhesive does have a very large beneficial effect on the compression creep failure rate, which is more closely related to warehouse stacking performance.

9. Wet strength linerboard and medium components did not affect either the laboratory box compression test strength or the compression creep rate.

10. This issue of the translation of laboratory test results into the expected field performance of corrugated boxes should always be of top concern to packaging engineers and package producers. There are no easy answers to this knotty translation problem that this author can offer, except for experience and caution. The laboratory is not the "real world;" it is just a very powerful tool for trying to deal with the complexities of real life.

Chapter 15

Package Rough Handling

It is estimated that approximately 90% of the packaged goods shipped to consumers in the United States are packaged in corrugated containers. The product must arrive at the consumers location undamaged and in one piece, if the package is to be judged as having performed its function. The package must block and cushion the product and protect it from drop or impact forces, (41). It must also contain the product. It is not nice to have cans of soup bouncing all over a parking lot.

As mentioned in the prior chapters, the handling of packaged products has changed dramatically over the past 30 years. Packaged goods are now usually unitized on a pallet or slip sheet and moved by the use of warehouse trucks. In the distant past of the 1960s, many boxes were still handled one at a time. Package testing laboratories were equipped with large revolving drums, fitted on the inside with baffles. Boxes were routinely tumbled in these drums to see if the package could withstand the rigors that existed in the field distribution cycle prevalent in those years. Today, most packaging engineers have never seen the drum test being run.

However, scoreline tearing still occasionally occurs. Research at the Institute of Paper Science and Technology has shown that the scoreline separation failure in a corrugated box starts by the tensile failure of the combined board at the scoreline. Once the failure has started, it continues to progress by tear failure along the scoreline. The corrugating medium, because of its fluted structure, contributes to the CD tensile strength of the combined board, but not to the MD tensile strength. In a typical RSC-style box, the medium would then contribute to the tensile strength of the flap scores of the box, but not to the body scores of the box. The medium contributes to the combined board tear strength in both directions.

Figure 15.1 shows the effect of corrugating medium basis weight on the ability of the filled box to withstand being dropped without breaking open. The boxes were dropped from a height of 12 inches onto a corner of the box. The plot shows the number of drops that were made before box failure occurred as a function of the medium basis weight. The data indicate that box drop strength performance improves as the corrugating medium basis weight increases. However, there is considerable scatter in the data points, (73, 82).

Figure 15.2 shows the same box drop test data plotted against the average Elmendorf tear strength of the medium. The data show that a stronger tear strength medium improves the drop test performance of the box. There is much less scatter in this strength data than was seen for the basis weight data in ***Figure 15.1***, (73, 82). This reinforces the point, that was made several times before in this reference publication, that material performance should be based on material strength levels and not basis weight.

The effect of flute size on the box drop test performance is shown in ***Figure 15.3***. The same linerboard and medium materials were used in both flute size boxes, and the boxes were manufactured at the same time in a commercial box plant. The C-flute boxes performed better in the corner drop test than the B-flute boxes, (73, 82).

The ability of corrugated board to act as a cushioning material is a more complex issue. The cushioning qualities of corrugated board involve the flat crush characteristic of the fluted medium and the design of the package. The cushioning function is provided by both the primary shipping case and any special inserts that may be used inside the box to protect the product, (28, 41, 103, 123).

A material acts as a cushion by absorbing kinetic energy in a controlled manner with time. Kinetic energy is the energy that any moving object has due to the combination of its mass and its velocity, (28). A simplistic example of the interaction of these properties and forces may be useful. An electric light bulb can be dropped on a concrete floor from a height of 1/2 inch, and it will probably not break. If the same light bulb is dropped on the same concrete floor from a height of 4 feet, it will probably shatter into hundreds of pieces of glass. If the same concrete floor is covered with an inch thick, plush carpet, and the same light bulb is dropped on it from a height of 4 feet, the bulb probably will not break.

FIGURE 15.1
Effect of Medium Basis Weight on Box Corner Drop Performance. (82)

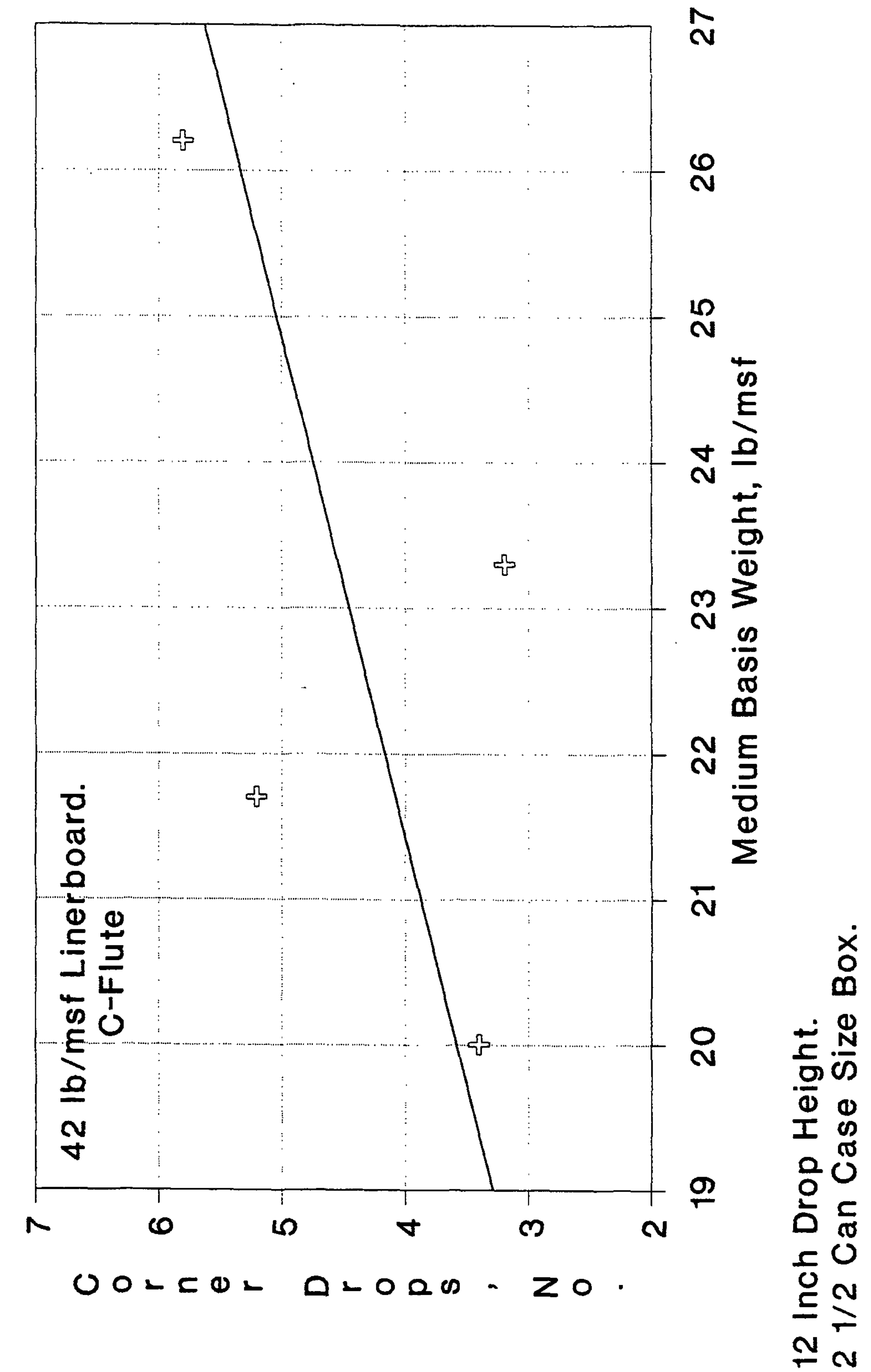


FIGURE 15.2

Effect of Medium Elmendorf Tear Strength on Box Corner Drop Performance. (82)

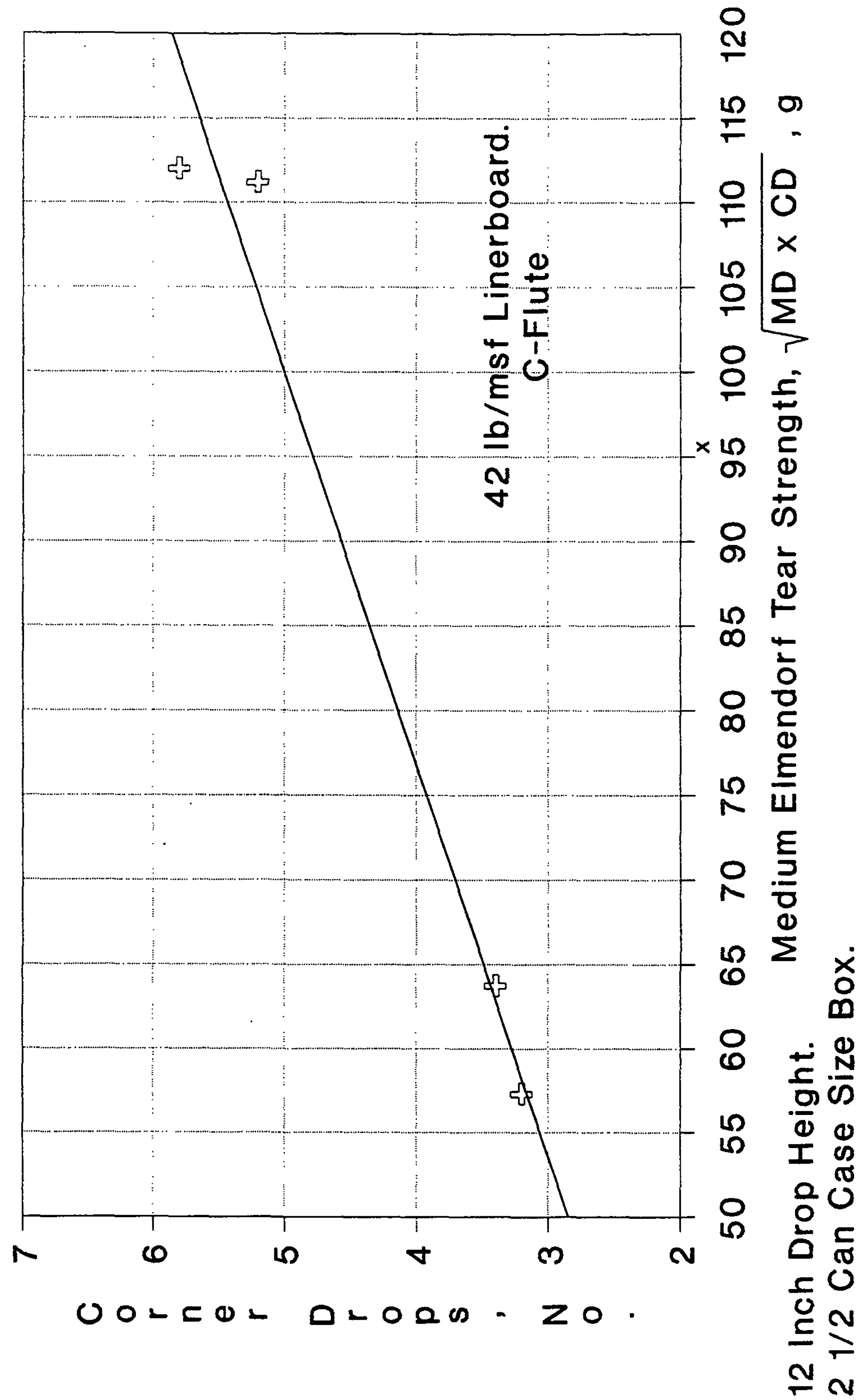
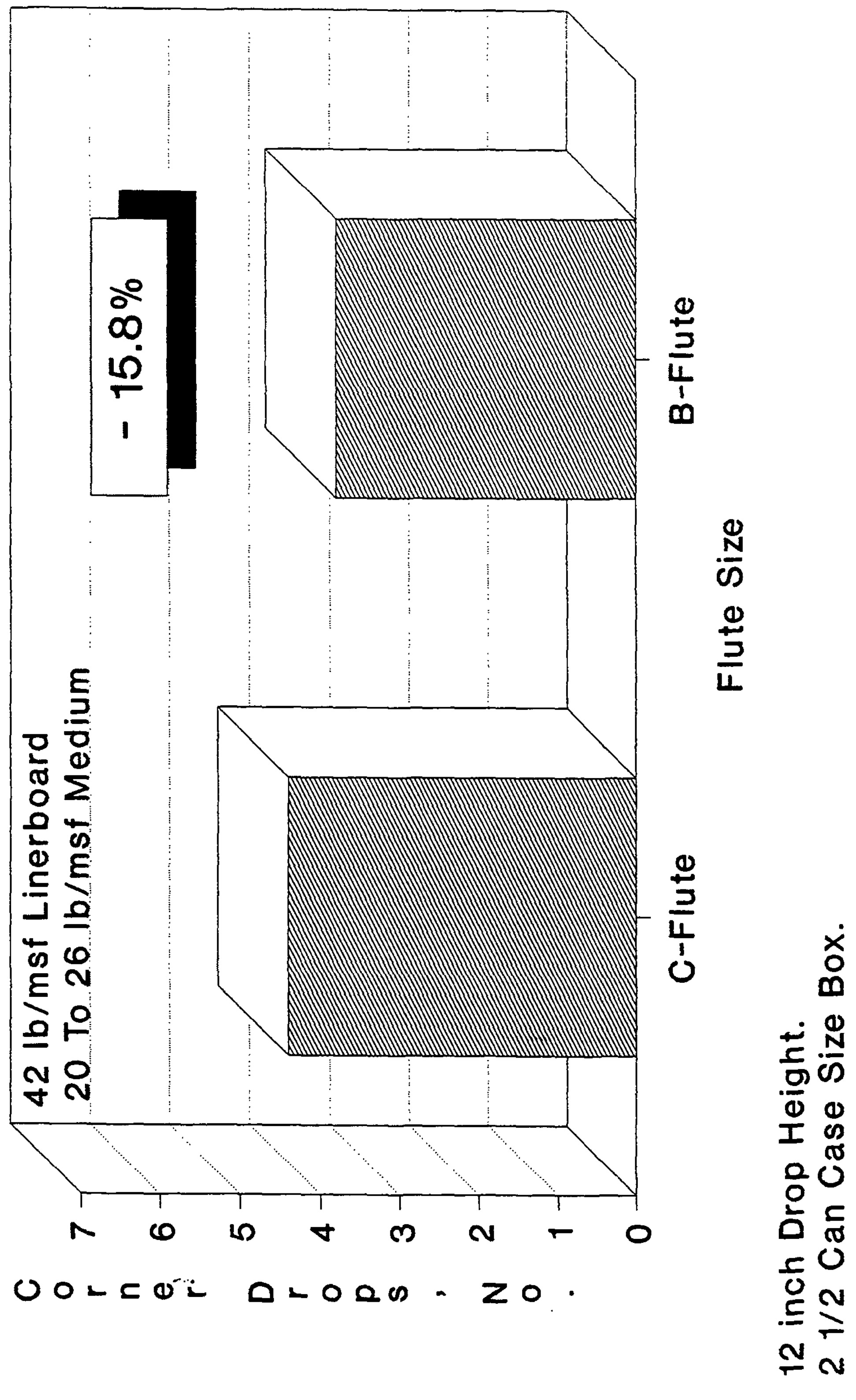


FIGURE 15.3
Effect of Flute Size on
Box Corner Drop Test, (82)



The kinetic energy of the light bulb at the time that it hits the floor depends on the drop height. The kinetic energy is imparted to the light bulb by the force of gravity. At a low drop height, the bulb has a low kinetic energy when it hits the floor because the force of gravity has had only a short time to act on the bulb. The higher the drop height, the higher the kinetic energy, and the higher the kinetic energy, the greater the probability that the light bulb will break. However, the light bulb has the same kinetic energy when dropped from 4 feet whether it lands on concrete or on a carpet. The light bulb does not break when it hits the carpeted floor because the carpet can absorb some of the kinetic energy by having the nap of the carpet deform. As the carpet deforms, the light bulb has more time to slow its speed and to stop falling. A longer deceleration time requires a lower maximum deceleration force to stop the fall of the bulb. With a lower deceleration force, the light bulb has a lower probability of breaking. The concrete floor has no give. The light bulb must stop almost instantaneously. The instantaneous stopping requires that a very high deceleration force be applied to the light bulb by the concrete floor. The high deceleration force breaks the light bulb. Life should always be this simple.

Figure 15.4 shows typical flat crush stress/strain curves for C-flute corrugated board where the flutes have been precrushed to varying degrees. The combined board flat crush property that is important to cushioning is not only the maximum flat crush strength, but also the flat crush energy. The flat crush energy is equal to the area under the curve, that is, the stress times the strain. The original, zero precrushed combined board has a flat crush energy of 17.5 units. A 20% precrush reduces this flat crush energy to 14.0 units, a loss of 20%. Similarly, a 40% precrush reduces the energy by 38%, and the 50% precrush reduces the energy by 83%, (59). If the kinetic energy of the falling object exceeds the flat crush energy of the combined board in the area contacted by the falling object, the flute structure will be completely collapsed. The falling object will "hit bottom" and may very well be damaged. The major conclusion from the data shown in ***Figure 15.4*** is that the crushing of the flute structure of corrugated board has a very adverse effect on the cushioning capability of the combined board.

Figure 15.5 shows that the crushing damage to the flute structure is made worse by repeated application of a constant crushing force to the same area of the corrugated board, (130). ***Figure 15.6*** shows the effect of repeated impacts on the maximum stress (deceleration force) imparted to the falling object by the corrugated board acting as a cushion material. A higher deceleration maximum stress level increases the probability of damage to the falling product. The maximum stress increases rapidly with repeated impacts and then starts to level off in this experimental example after 10 impacts, (128). The leveling off indicates that the entire flute structure has been destroyed. The falling object has "hit bottom."

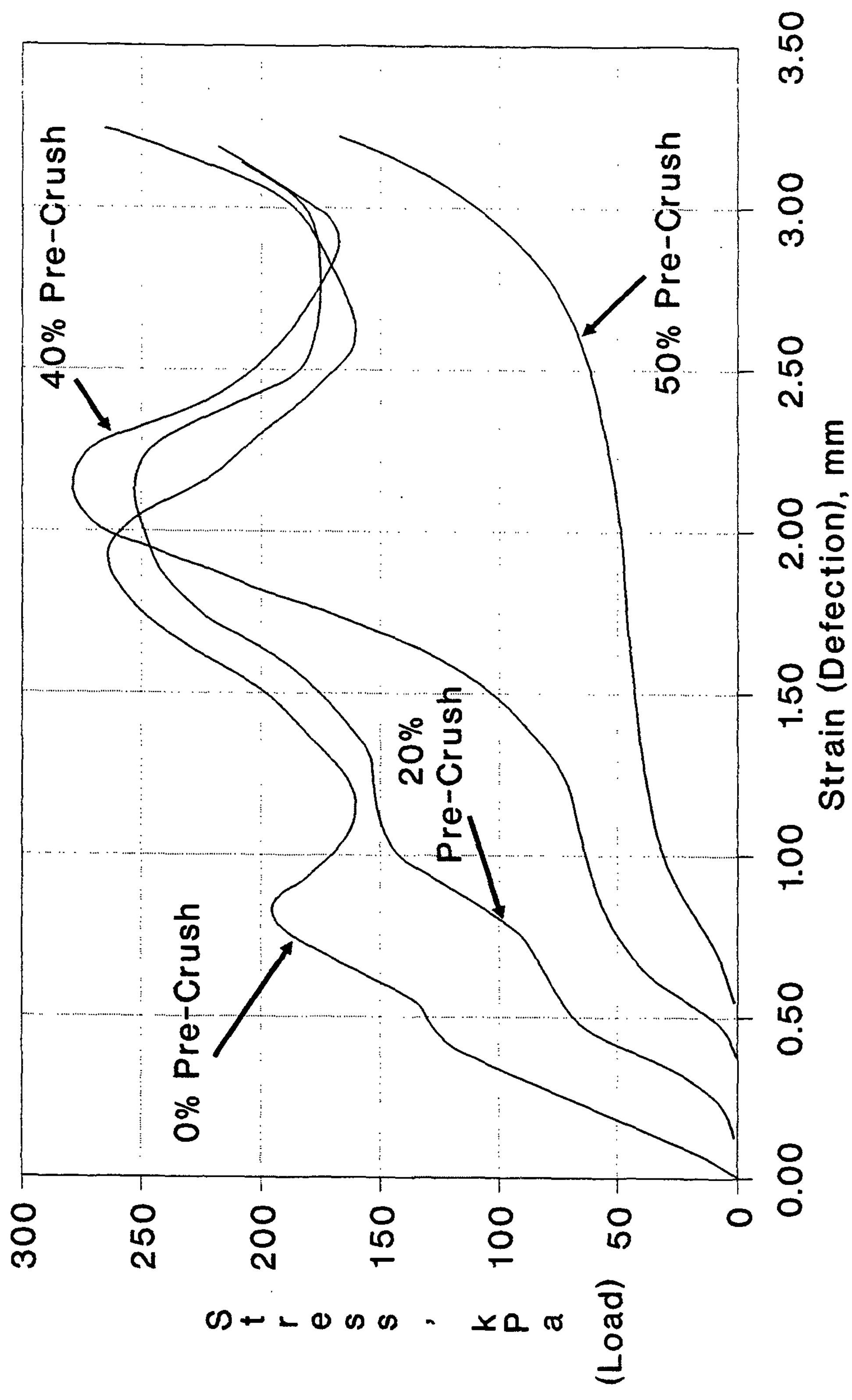
The effect of the corrugated board flat crush strength and the number of corrugated board plies on the maximum static stress that can be sustained at a deceleration level equal to 200 times the force of gravity (200 G) is shown in ***Figure 15.7***. Static stress is a fancy engineering term for the load per unit area. The data show that a corrugated board with a higher flat crush strength has better cushioning ability. More layers of corrugated board also improve the cushioning ability. More plies of corrugated board provide a thicker structure that can be crushed by the falling object. This provides more time to stop the object and allows a lower maximum stopping force (for the true "Techy" types, Force x Distance x Time = Work). The data show that a higher flat crush strength can be traded off against the number of corrugated board plies needed to achieve a specified level of cushioning. Based on the data shown in ***Figure 15.7***, two layers of corrugated board with a flat crush strength of 3.0 kp/sq.cm. can be substituted for three layers of corrugated board with a flat crush strength of 1.0 kp/sq.cm., (123).

Figures 15.8 and 15.9 show the effect of medium basis weight, linerboard basis weight, and the number of corrugated board layers on the maximum measured deceleration force with a 1 psi static load being applied. The 1 psi static load is well within the elastic region of the flat crush stress/strain curve for the corrugated board grade used in this study. The data show that increasing the medium basis weight from 26 lb/msf to 33 lb/msf resulted in a 94% increase in the maximum measured deceleration force. The effect of the linerboard basis weight and the effect of the number of corrugated pad plies were much less, (103). Based on the prior data, it would appear that a lower deceleration force would be advantageous, and fewer pads, lower basis weight linerboard facings, and lower medium basis weight would be better.

That is true if a product is being dropped on a piece of corrugated board. However, the product in question is usually packed inside of the corrugated box, and the box acts as a buffer between the forces of the outside world and the valuable product. In this scenario a corrugated board that can absorb more energy will better protect the product from an outside impact force. As a rule of thumb, a soft, giving corrugated pad is best for inner packing since it acts as a cushion for the product against transportation shocks, such as acceleration and deceleration. However, it must have enough guts (energy absorption power) so that it does not crush down completely and lose all of its cushioning properties. The corrugated box, on the other hand, acts as a buffer to the impact forces of the cruel outside world, such as a person kicking the side of the box. This buffer role requires the high

FIGURE 15.4

Effect of Combined Board Crushing on the Flat Crush Stress/Strain Curve. (59)



C-Flute Corrugated Board.

FIGURE 15.5
Effect of Multiple Crushing of Combined Board on Measured Caliper Loss, (130)

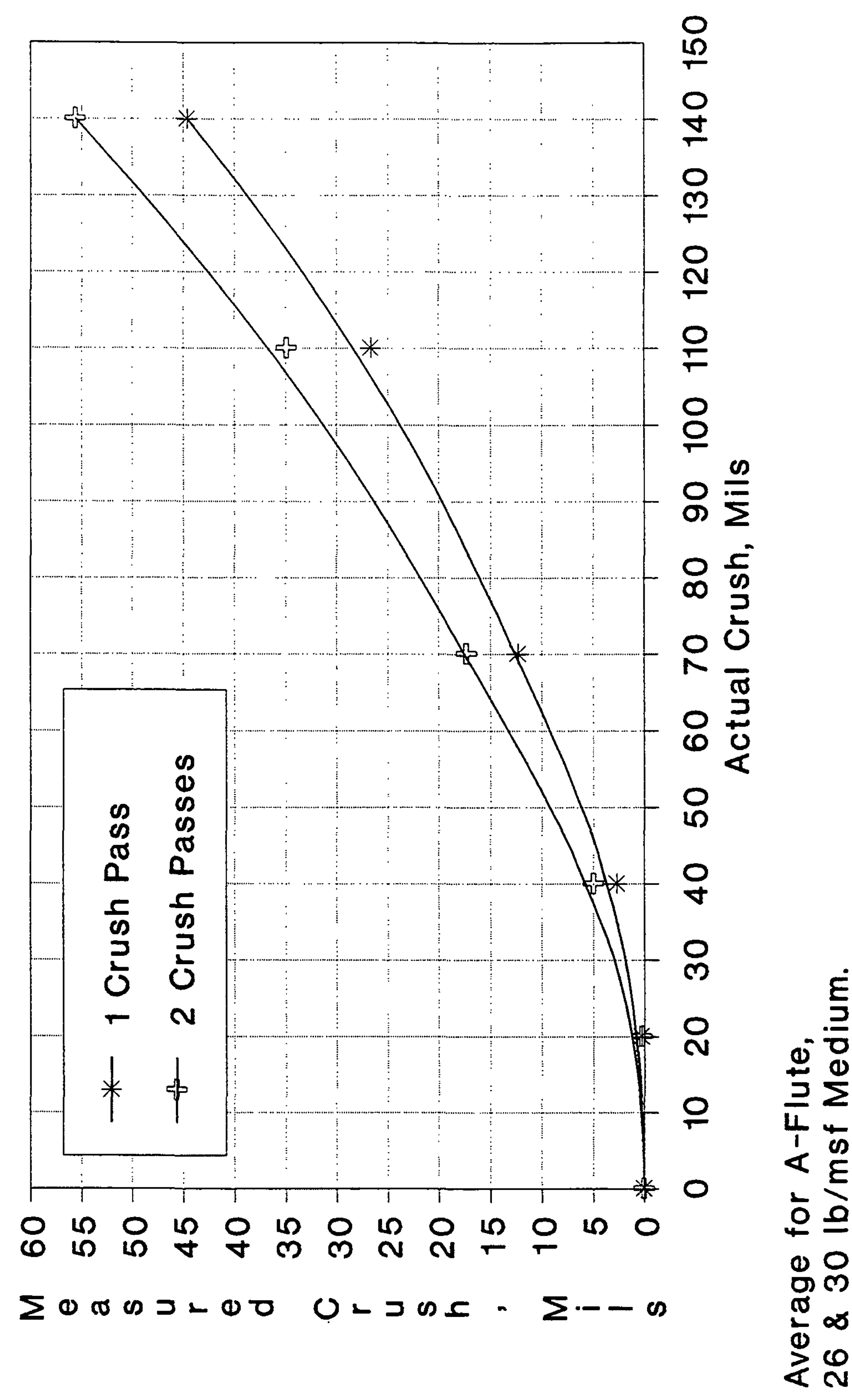


FIGURE 15.6

Effect of the Number of Impacts on the Maximum Measured Stress, (128)

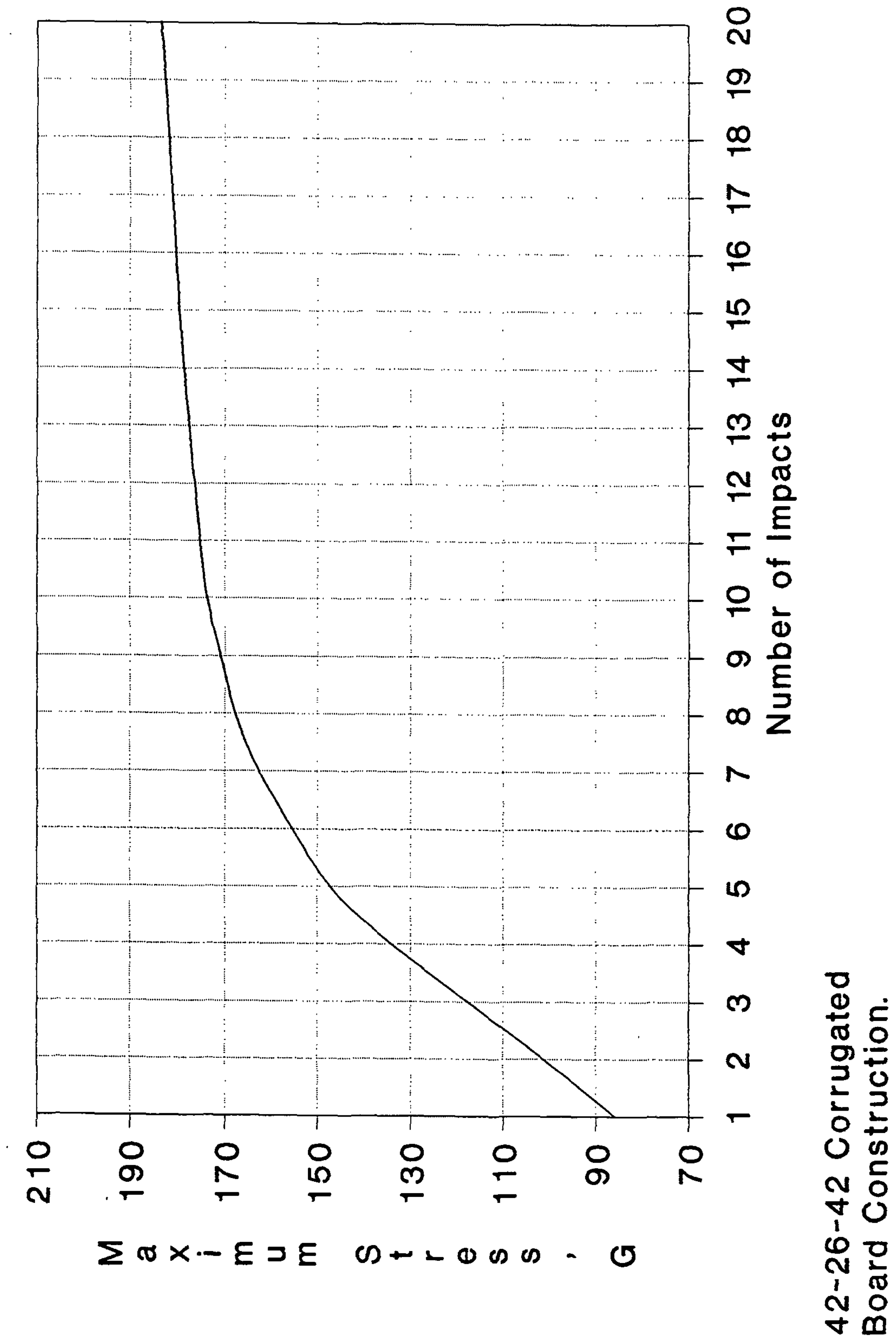
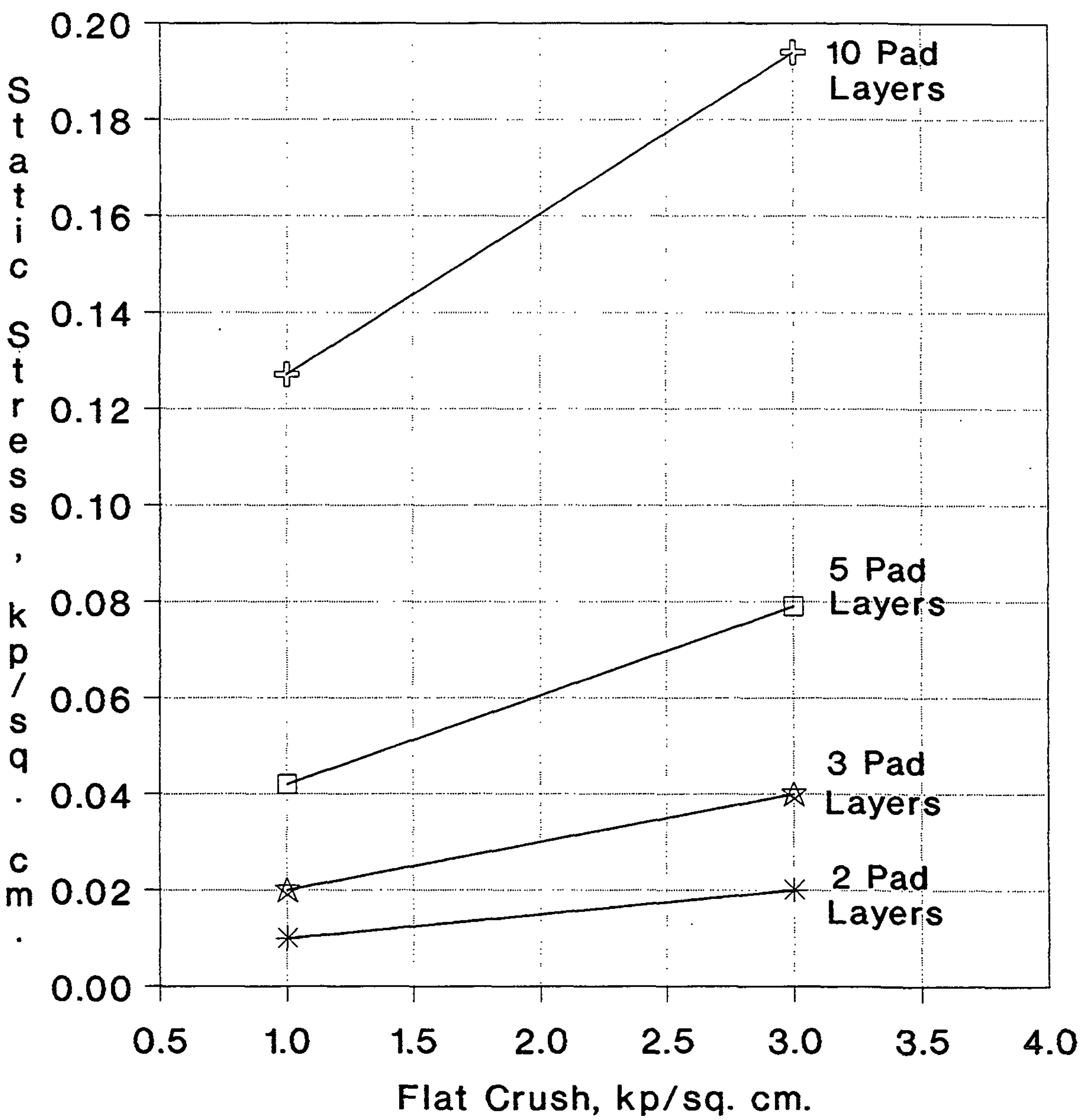
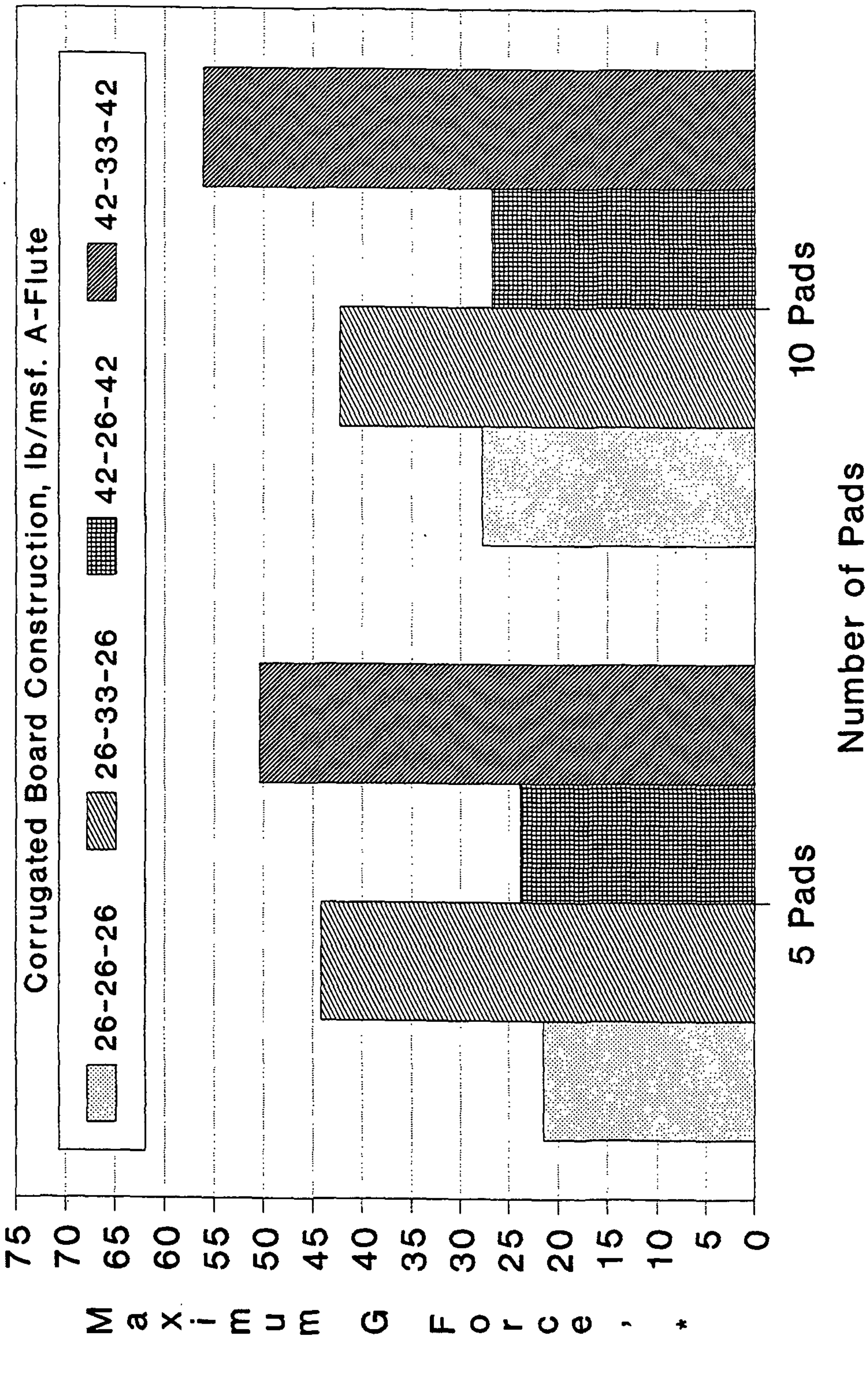


FIGURE 15.7
Shock Force Absorbing Characteristics of Corrugated Board - Effect of Combined Board Flat Crush & Number of Layers, (123)



Box Drop Tests From 61 cm.
and 200 G Peak Deceleration.

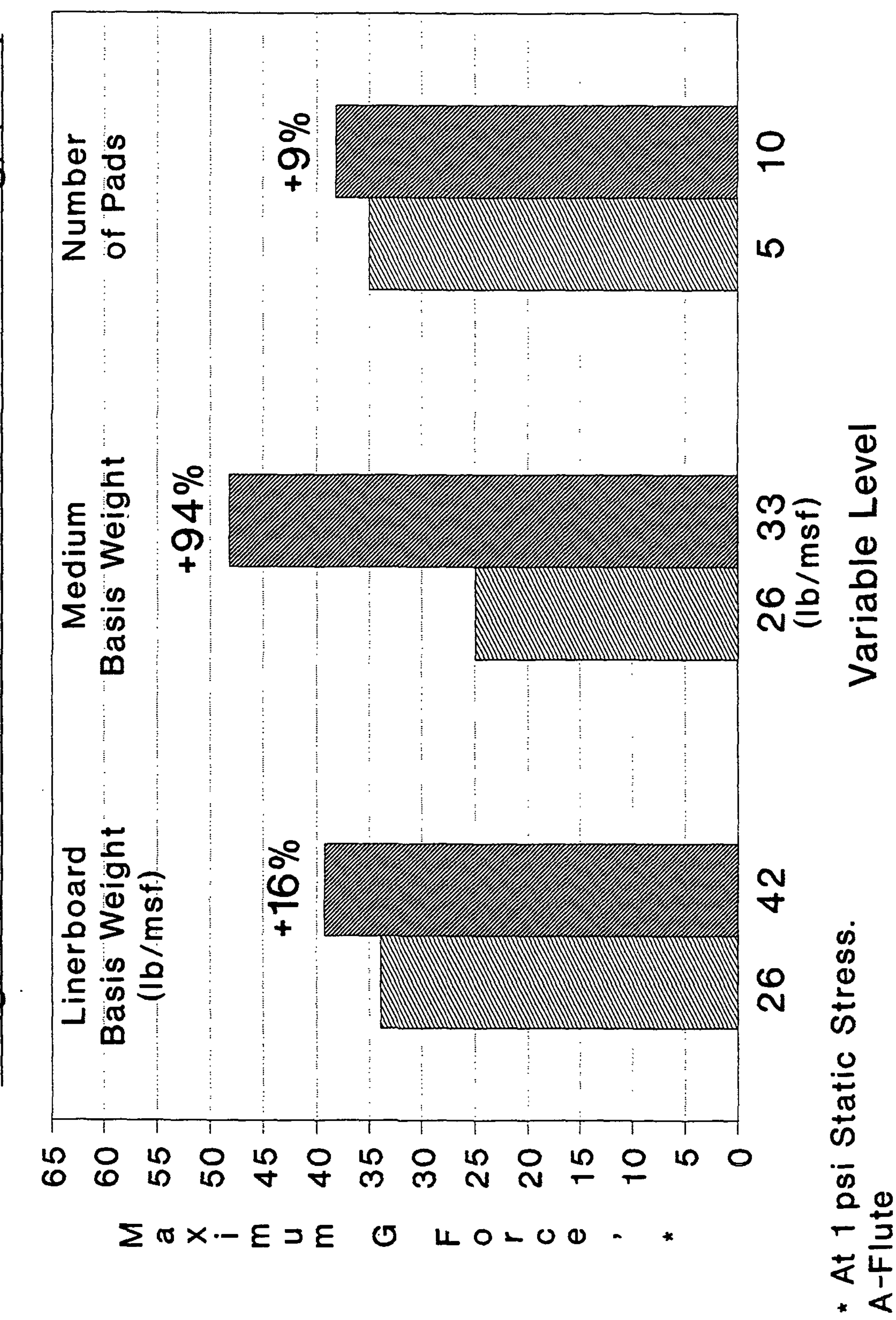
FIGURE 15.8
Effect of Medium & Linerboard Basis Weight and Number of Pads on Cushioning. (103)



* At 1 psi Static Stress.

FIGURE 15.9

Effect of Medium & Linerboard Basis Weight and Number of Pads on Cushioning. (103)



energy absorption capacity provided by the higher flat crush strength medium. It was mentioned before that cushioning is a very complex subject.

Figures 15.10 and 15.11 show the effect of corrugated board pad designs on cushioning capability. There are literally hundreds of different designs in use today. The two shown, "Spring Pad" and "Folded Pad," are two of the more common designs currently being used commercially. The experimental data show that the cushioning effectiveness of the spring pad design is independent of the package size. The folded pad design becomes more effective as the package size decreases.

The technical information presented in this chapter supports the following observations with regard to package rough handling characteristics.

1. A package must block and cushion the product and protect it from drop or impact forces. It must also contain the product.

2. A stronger tear strength medium improves the drop test performance of the box. C-flute boxes performed better in the corner drop test than the B-flute boxes.

3. The ability of corrugated board to act as a cushioning material is a very complex issue. The cushioning qualities of corrugated board involve the flat crush characteristic of the fluted medium and the design of the package. A material acts as a cushion by absorbing kinetic energy in a controlled manner with time.

4. The combined board flat crush property that is important to cushioning is not only the maximum flat crush strength, but also the flat crush energy. The flat crush energy is equal to the area under the flat crush stress/strain curve.

5. Crushing of the flute structure of corrugated board has a very adverse effect on the cushioning capability of the combined board. The crushing greatly reduces the available flat crush energy.

6. As a rule of thumb, a soft, giving corrugated pad is best for inner packing since it acts as a cushion for the product against transportation shocks, such as acceleration and deceleration. The corrugated box, on the other hand, acts as a buffer to the outside impact forces, such as a person kicking the side of the box. This buffer role requires the high energy absorption capacity provided by the higher flat crush strength medium.

7. The cushioning effectiveness of the "Spring Pad" design inner packaging is independent of the package size. The "Folded Pad" design becomes more effective as the package size decreases.

FIGURE 15.10
Effect of Pad Design on Cushioning

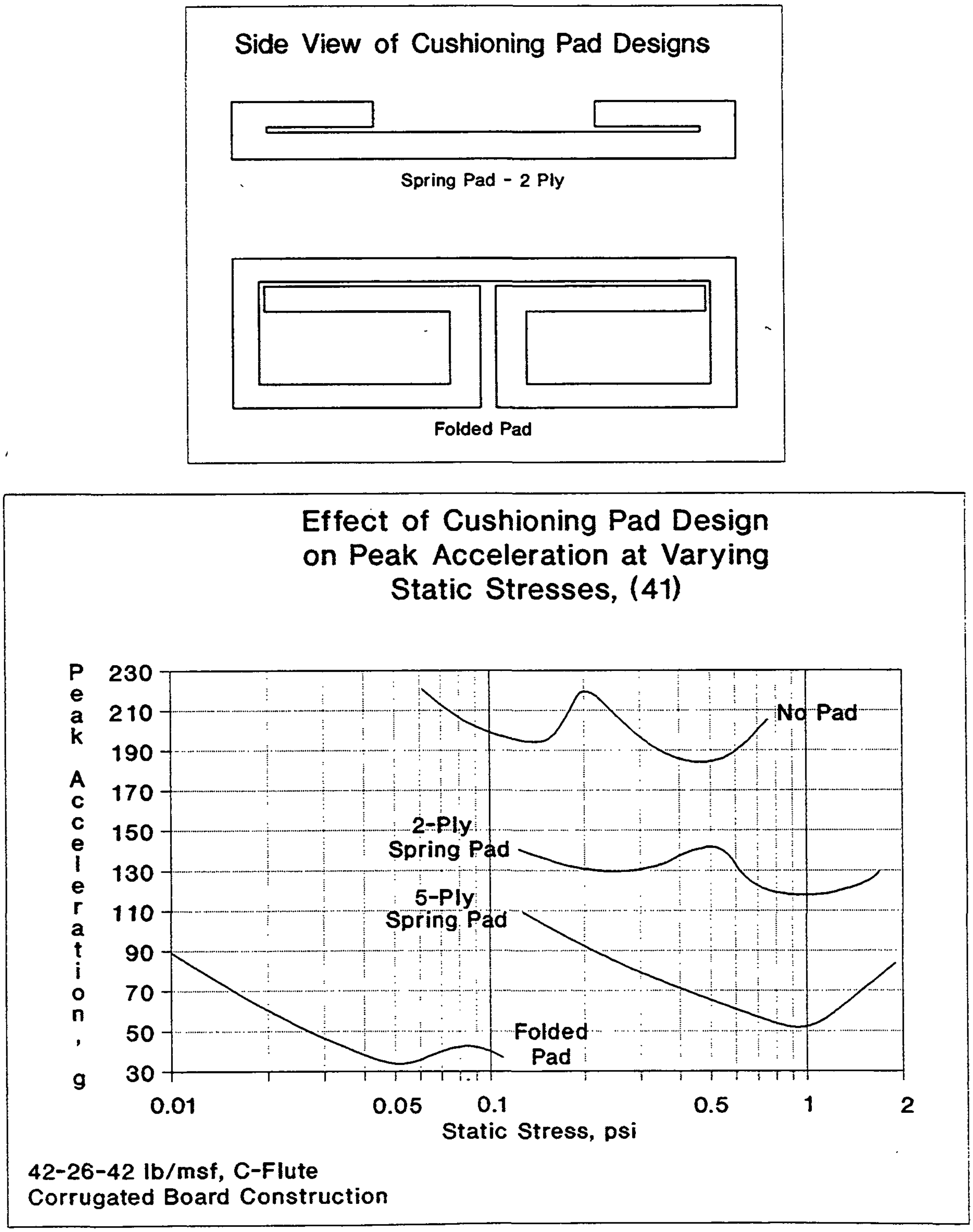
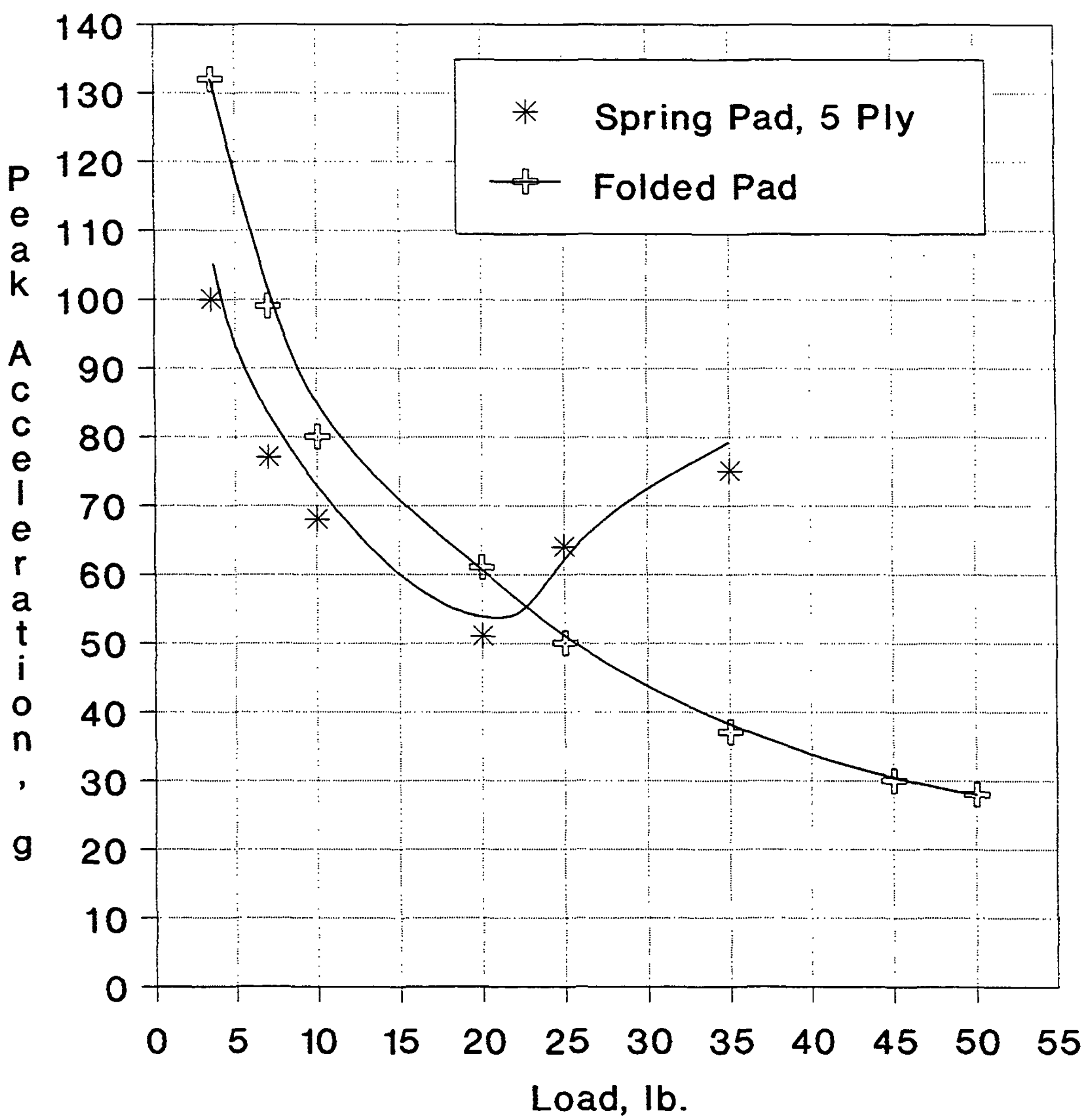


FIGURE 15.11
Impact Load Effect on Peak Acceleration for Various Cushioning Pad Designs, (41)



42-26-42, C-Flute
Corrugated Board

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