Institute of Paper Science and Technology

# SIMULATION OF A LINERBOARD PAPER MACHINE

**Project 3471**

**Report 5**

**to**

**MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY**

**September 1992**

Atlanta, Georgia

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INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

# SIMULATION OF A LINERBOARD PAPER MACHINE

Project 3471

Report 5

A Progress Report

to

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

By

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September 1992

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## ABSTRACT

A detailed model was developed of a two-ply linerboard paper machine using the MAPPS process simulation program with performance attributes (PATs). The model realistically predicted the sensitivity of liner compressive and tensile properties to furnish composition i.e., OCC content, refining, power pressing load, fiber orientation, formation, and machine restraint. For most process variables, burst and CD ring crush display a similar sensitivity. However because burst depends on both MD and CD tensile strength and stretch while CD ring crush is more strongly dependent on CD elastic properties, these two measures of compressive strength show different sensitivities to fiber orientation and machine restraint (wet stretch). For example, when fiber orientation was predominantly in the cross direction, burst decreases with increasing MD strain while CD ring crush increases significantly. As fibers became oriented in the machine direction, the response is reversed with burst increasing significantly with MD restraint and CD ring crush decreasing with increased MD restraint. Both burst and CD ring crush are increased by factors which increase bonding such as increased press load and increased refining. Both are also improved by improved formation. Burst benefits from high MD fiber orientation and low levels of MD restraint or stretch. CD ring crush benefits from higher CD orientation and higher MD or CD restraint.

Edgewise compressive strength properties (e.g., CD Ring Crush) are sensitive to sheet elastic properties and caliper. At constant sheet basis weight and caliper, compressive strength is influenced by in-plane and out-of-plane elastic properties. Elastic properties are sensitive to bonding, fiber modulus, and residual stresses in the sheet. Residual stresses are, in turn, influenced by fiber orientation and wet strain. Compressive strength was quite sensitive to press loading, formation, restraint and fiber orientation. Refining, while significant, had a smaller effect than expected. Refining increased sheet bonding and fiber tensile strength and elastic modulus. Changes in these variables led to increased sheet modulus and compressive strength.

The results are based on a MAPPS model of a linerboard paper machine in an integrated Southern United States mill. The model was designed to accurately reflect the mill flowsheet and operating conditions. The base case was tuned using a small sample of mill machine property data and typical machine operating conditions. This report summarizes much of the available literature on the influence of furnish and process conditions on compressive strength, as well as, the methodology used in the sensitivity study.

## OBJECTIVES

The objectives of this study were:

1) to develop, through analysis of the literature, theoretical and experimental support for the relationship of compressive strength of linerboard to certain fiber properties and paper making process variables.

2) to develop a valid MAPPS simulation model of the two-ply paper machine.

3) to compute the sensitivity of several measures of compressive strength i.e., CD ring crush, CD STFI, and burst to important process conditions: OCC content, refiner load, press load, formation, restraints in forming and drying and fiber orientation.

4) to validate and correct deficiencies in the model and to identify fundamental problems for future work.

## SUMMARY

A review of the literature shows that edgewise compressive strength of paper including linerboard depends on the elastic properties and sheet caliper. Elastic properties are affected by fiber bonding and fiber modulus. Equivalently, edgewise compressive strength depends on specific elastic modulus. The specific modulus of the sheet is independent of sheet density and depends only on bonding and fiber modulus. Fiber bonding is primarily influenced (increased) by increased refining and wet pressing. Compressive strength is also increased by improved formation which tends to increase the effectiveness of the bonding levels. The contribution of the elastic properties to the compressive strength depends on built in stresses within the sheet which are created during forming, pressing, and drying through fiber orientation and machine restraint.

As MD fiber orientation increases, MD properties tend to increase, while CD properties tend to decrease. Densification of the sheet through calendering and wet pressing tends to reduce sheet caliper thus reducing the load-bearing area. Wet pressing increases both bonding levels and sheet density resulting in an increase in specific modulus. This leads to improved compressive strength. However, most normal calendering only increases bulk density and has little or no effect on bonding. Thus specific modulus is not changed and there is little or no effect on edgewise compressive strength.

The model used in MAPPS to predict compressive strength is based on mill and handsheet data (Whitsitt 10) and on models adapted from earlier work by Habeger (12) which correlate compressive strength to in-plane and out-of-plane ultrasonic elastic stiffness. In the MAPPS models used in this study specific elastic stiffness (or modulus) is assumed to be influenced by four variables: effective bond density, fiber modulus, fiber orientation, and wet stretch. Effective bond density is determined by wet densification conditions and formation levels.

The predicted compressive strength was most sensitive to changes in wet pressing, secondly, to fiber orientation and formation, third to refining level, and fourth to drying restraint. Surprisingly, the increased OCC content improved compressive strength somewhat. This is primarily due to a low freeness assumed for the OCC. The predicted compressive strength was not affected by calender loading in approximate agreement with expectations.

## INTRODUCTION

MAPPS, Modular Analysis for Pulp and Paper Systems, is a process simulation program for the pulp and paper industry developed by the Institute of Paper Science and Technology. Conventional process simulation techniques treat the papermaking process only in terms of the flow of mass and energy. Fiber structure, composition, and network development are not taken into account. The unique feature of MAPPS simulation is the ability to account for these important papermaking characteristics, making it possible to predict paper and board end-use performance characteristics, such as compressive strength. These fundamental fiber and network variables are referred to as performance attributes, or PATs. The prediction of end-use performance is called "performance attribute modeling."

Recently, the performance attribute modeling capabilities of MAPPS have been greatly extended to simulate sheet forming and end-use properties with multi-ply sheets. Concurrently, simulations for newsprint, medium, and fine paper production have shown the predictions of the system compare reasonably well with experimental data (37). Earlier work by Jones showed that performance attributes could be applied to modelling of fiber development in mechanical pulping systems and to predict the effects on handsheet properties of fiber recycling (37, 46). The MAPPS Performance Attribute System was also used to quantify the impact of processing conditions and sheet composition on brightness variations in fine paper machines in a proprietary application.

Jones also used the PAT system in MAPPS to track the response of some paper properties to changes in process variables such as OCC-content, refiner conditions, calender stack loading, third press loading, and machine speed for corrugating medium (22).

A more detailed long-term project will assess the transient response of the current linerboard process model to real-time data variations and compare the model predictions to mill laboratory data. The model will be run on line using a specially designed version of MAPPS as part of the mill's PI (Oil Systems Inc.) information system. MAPPS will receive live data input from PI and will pass predictions back to the PI database in the form of computed tag values. An analysis of the predicted and measured data will be used to determine model validity, sensitivity to process conditions, and to point to model improvements.

## LITERATURE REVIEW

### Measuring Compressive Strength

Compressive strength is an important end-use requirement for corrugated containers. With the introduction of the modified Rule 41, compressive strength has become an important quality specification for corrugated board, replacing the traditional burst strength test. As a result, manufacturers are now interested in determining the sensitivity of compressive stength to process conditions.

The following factors are important when measuring edgewise compressive strength:

- Failure should not be initiated by bowing or buckling.
- There should be a range of test spans wherein the maximum load is approximately constant (intrinsic compressive strength).
- Failure should not occur along the loaded edges or clamps.

A number of methods for measuring edgewise compressive strength are in use. The maximum strength obtained varies depending on how well the method meets the above criteria. The test methods are of three general types: 1. cylinder type, 2. strip columns, and 3. laterally supported columns.

For purposes of this review, only two tests, Ring Crush (the historical standard) and the newer short span or STFI test, will be considered. These two methods have been compared recently as part of a project sponsored by the Container and Kraft Paper Group of the American Paper Institute (62). Some of the following comments are taken from this detailed critique. The Ring Crush test, which falls into the first category, is perhaps the most common way to measure compressive strength in the industry.

In the Ring Crush test (TAPPI T818 os 76), a die-cut 0.5 by 6 inch specimen is inserted in a circular holder which supports the specimen in a cylindrical shape. The half-inch dimension is parallel to the CD direction. Failure usually involves buckling of the cylindrical specimen walls or crushing of the specimen edges. Ring Crush is a relatively complex phenomenon because of the cylindrical geometry and the complex mode of failure. Because the load in the ring crush test is applied at the edges, any imperfections in the edges resulting from cutting may affect the load at failure. Also it may be difficult to maintain a parallel alignment of the loading beam, lower platen and the surfaces of the ring crush holder and the upper and lower platens. For light-weight materials (especially 26 pound grades), failure occurs by buckling, while for heavy weight materials (heavier than liner grades), the sample cannot be bent into the required ring shape without causing bending failure. Also the edges of the specimen may be weakened by cutting during preparation of high basis weight specimens.

The strip column test developed by the Swedish Forest Products Laboratory, the STFI short-span compression test, is designed to measure compression strength at a short span of 0.7 mm. In this test the specimen is cut 15 mm wide and any convenient length, usually 3 inches or more. The longer dimension is chosen to be parallel to the cross machine direction. The specimen is then gripped between two pairs of clamps separated by a distance of 0.7 mm. As the clamps are moved together, they exert a compressive force resulting in a buckling failure. The STFI test has been criticized for its relatively complex calibration procedures. The clamps must achieve a high friction coefficient and be precisely aligned. The loads obtained are higher than those obtained with most other methods.

Due to the similarity of the buckling failure, it is possible to correlate the Ring Crush and STFI test results over a range of board weights. However, such relationships may not hold under all papermaking conditions. Ring Crush and short-span STFI compression test results exhibit significantly different MD/CD ratios. This indicates the tests are affected differently by such paper making factors as fiber orientation and wet strain. (4)

**Sheet Characteristics**

According to Paulapuro and Thorp (1) and Sozynski and Seth (6), edgewise compressive strength is affected by the following basic sheet characteristics:

- Fiber-to-fiber bonding
- Elastic properties
- Fiber Stiffness
- Thickness
- Formation
- Fiber orientation
- Sheet cleanliness

The effect of board manufacturing variables and fiber properties on compressive strength can be understood through their effects on these basic characteristics. As will be shown, these process conditions have multiple and interactive effects on these basic characteristics.

**Fiber Bonding.** Linerboard compressive strength is primarily affected by fiber-to-fiber bonding. Increased bonding improves the sheet elastic modulus (as will be discussed later). Compressive strength has been related theoretically to elastic modulus as an unstable buckling phenomenon. Experimentally determined values of elastic modulus have also been shown to correlate strongly to various measures of compressive strength.

The most important factors involved in fiber bonding are the area of the fibers in contact, the number of bonds within the area of contact, and the strength of each bond. A factor describing the bonded area, the relative bonded area, is defined as fiber bonded area divided by the total area available for bonding (i.e., the area of totally unbonded fibers). The strength of fiber-to-fiber bonding has been determined both as the energy of bonding and as the force required to rupture bonds. The specific bond strength has been found to be relatively constant and independent of species and pulping conditions.

The degree of bonding depends on the chemical and physical nature of the fiber surface and upon the manner in which the fibers have been formed into the sheet. The mechanical treatment which the fibers undergo in the beating process changes all of these factors. Along with refining, wet pressing is the major factor affecting fiber bonding. Also, the morphology of the pulp fibers, notably the cell-wall thickness, influences the conformability of the fibers and indirectly affects relative bonded area. In addition, interfiber bonding is influenced by the chemical composition of the wood pulp, particularly hemicelluloses and lignin. It is possible that the degree of polymerization of the cellulose also has an effect, at least indirectly. The presence of alumina, sizing, fillers, and other additives also affect interfiber bonding. The process of repulping and reclaim of secondary fibers and the recycling of fibers affect many of the factors controlling fiber bonding (25).

Under most papermaking conditions, an increase in density is accompanied by an increase in fiber bonding. Thus, edgewise compressive strength increases in approximately a linear fashion with density. as shown in Fig. 1 (2, 4).

According to experiments by Seth, Sozynski, and Page (2), however, compressive strength depends strongly on bonding only at relatively low bonding levels. As bonding increases, a limiting strength is reached that is independent of further increases in bonding. This behavior is similar to that of tensile strength as described by Page. One interpretation of these results is that at high degrees of bonding compressive strength of paper is controlled by the compressive strength of individual fibers. It is important to note that because the compressive strength of paper is only about 30-40% of its tensile strength, the degree of bonding required to reach the plateau in compressive strength is much lower than that for tensile strength. For all pulps compressive strength expressed as breaking length increases as the pressing pressure (i.e., bonding level) is increased up to about 4 km where it levels off. In conventional units this is equivalent to 39 Nm/g. This level is remarkably constant for all yields. The plateau is unaffected by beating, but with increased beating compressive strength is generally higher at equivalent pressing pressures.

**Elastic Properties/Elastic Constants.** When paper is subjected to tensile stress, it behaves for small strains as an elastic material. The elastic modulus (Young's modulus), generally determined from the initial slope of the load-elongation curve, is an important mechanical property of paper. It is a critical end-use property of certain products and provides an understanding of other strength properties.

The elastic properties of any material can be characterized by elastic constants such as Young's modulus, relating stresses and strains. This characterization is often made in terms of the engineering constants of Young's moduli (E), shear moduli (G), and Poisson's ratios. The stress-strain relationship of paper can also be expressed in terms of the actual elastic constants (C) or compliances (S) of the material. For the interpretation of ultrasonic measurements, it is often most convenient to characterize a material in terms of its actual elastic constants (C).

Paper may be described as a three-dimensional orthotropic material, i.e., a material whose properties vary in each of the three mutually perpendicular symmetry planes. The normal directions to these planes are the machine direction (MD), cross-machine direction (CD), and the thickness direction (ZD). Occasionally, these three axes are also designated as X, Y, Z or as 1, 2, 3. The properties of paper are different along each of these axes. Figure 2 shows the convention used to relate these different types of notation for paper.

The subscripts referring to the stress directions are given as single or double subscripts. In the double subscript used, the first subscript refers to the direction of the normal to the surface on which the stress is acting; the second subscript refers to the direction in which the stress is acting.

An orthotropic material is characterized by nine independent engineering elastic constants: three Young's moduli, three shear moduli, and three Poisson ratios. Two Young's moduli, E1 and E2, define stress strain relationships in the MD-CD plane. The third Young's modulus, E3, defines the out-of-plane or ZD (thickness direction) stress-strain relationship. The three shear moduli, G1, G2, and G3, express the relation between shear stress and shear strain in the three directions. The Poisson ratios are defined as the relationship between passive strain and active strain as paper is strained.

The engineering elastic constants can be measured mechanically with an Instron type device. Engineering elastic constants are generally somewhat lower than actual elastic constants (C). The compliance constants, S, are the inverse of actual elastic constants ($C = 1/S$) and relate the strains as functions of stress. The constants directly measured with the speed of ultrasonic waves in paper are the actual elastic constants or C's. The engineering E's can be, and often are, calculated from the ultrasonic constants taking into account the Poisson effect, i.e., the effect of passive, induced strain. The calculated engineering constants still are somewhat larger than mechanically measured ones. The reason for this is found in the dependence of the viscoelastic behavior of paper on the rate of strain. In the mechanical device, the lower rate of strain results in a significant time-dependant viscoelastic behavior which does not occur with relatively fast ultrasonic measurements. The strong dependence of modulus on frequency (51) also indicates that under some conditions viscoelastic effects can become important.

Paper is actually characterized by nine elastic constants, nine compliance constants, and nine engineering constants. The actual elastic constants, $C_{11}$, $C_{22}$, and $C_{33}$, relate the normal strains to normal stresses and are close approximations to the three Young's moduli. The shear constants, $C_{44}$, $C_{55}$, and $C_{66}$, relate shear strains to the shear stresses and are identical to the engineering shear constants. The Poisson's ratios are most closely related to $C_{12}$, $C_{13}$, and $C_{23}$. The nomenclature of the three different types of constants is often somewhat inconsistent in the literature. (41)

The modulus most often referred to is that in the MD direction. Young's modulus in the MD direction is typically twice that of the CD direction. The Z-direction Young's modulus is considerably smaller than the in-plane values presumably because of the layered structure of paper.

The moduli are functions of fiber orientation, drying restraints, density, and beating. A papermaking variable producing a change in properties in one direction alters the properties in the other two directions in a predictable way. The effects of wet straining in the MD to gain stiffness or strength results in significant decrease in these properties in the CD and particularly in the ZD direction. A moderate strain of 2.4% results in a 50% reduction in the ZD stiffness. The in-plane shear modulus and the Poisson ratios are found to be insensitive to wet straining and decrease somewhat with increasing fiber orientation (27).

Ultrasonic measurements of elastic constants actually determine the velocity, v, of the appropriate sonic wave in the direction of interest. In general, the specific stiffnesses are proportional to $v^2$. The specific stiffness is defined as the modulus, C, divided by density, $\rho$, which is also equal to stiffness (Ct) per unit of basis weight where t is the sheet caliper. The specific stiffness can be transformed to stiffness, Ct, or moduli, C, by multiplying $v^2$ by either basis weight or density, respectively.

**Elasticity Theories of Paper.** The starting point for many theories of the elastic modulus of paper is the work of Cox (24). He considered paper as a two-dimensional network of randomly oriented, long, straight, linearly elastic fibers. He initially assumed that the stress distribution within the sheet was homogeneous so that the strain in every fiber was equal to the local strain of the sheet in the fiber direction. From an analysis of strains and resolved stresses in fibers, he concluded that the elastic modulus of paper is equal to one-third of the elastic modulus of its component fibers.

Page (26) showed that the elastic modulus of pulp softwood fibers in the most common range of fibril angles, 0-20 degrees, is about 4.5 to 5.5 GPa. This value is surprisingly independent of pulping chemistry and yield in the range generally used. Page (13) also determined experimentally that the highest moduli of paper indeed correspond to Cox's theoretical value or one-third of the modulus of fibers.

The modulus of paper usually falls short of the theoretical one-third of the fiber modulus. Page, Seth, and De Grace (13) starting from Cox's theory discuss the reasons for this deviation thus expanding the factors affecting the modulus of paper. Their theory puts together the three mechanisms that, it is believed, are entirely responsible for the variations. The effect of these mechanisms is best summarized by reference to Fig. 3. In the figure it can be seen that for well-bonded sheets of long, straight fibers, the modulus of the sheet is of the order of one-third of the modulus of the fibers as predicted by Cox. This level is not reached either due to "nonideal fiber modulus" or to a low degree of bonding. Since fibers are of finite length, stress must be transferred from each fiber to its neighbors in the regions of fiber ends. The stress in each fiber has its maximum at the center and diminishes to zero at the fiber ends. Thus, the fall-off in stress will depend on the shear modulus of the matrix. This causes the elastic modulus to fall short of the theoretical value by an amount that depends on the ratio of the length over which the stress is transferred to the fiber length. If we consider sheets of different degrees of bonding, it is expected that the higher the degree of bonding, the shorter the length over which transfer of stress would occur. The increase in modulus with bonding may thus be seen as a more efficient utilization of the entire fiber length because it reduces the length of the fiber used for stress transfer. A third factor may be the presence of curl, kinks, crimps, and microcompressions in the fibers. These lower the modulus of the sheet unless removed by beating or by drying the sheet under restraint.

This field has proved to be a rich source of new theoretical approaches. Nissan and coworkers devised elasticity theories of paper based on hydrogen bonding theory (60). Schulgasser and Page showed that the transverse modulus of fibers when combined with the constant strain theory of Cox could explain many of the discrepancies seen in the use of the original theory (61). Kallmes and coworkers (53) evaluated various fundamental theories in studying the elastic behavior of paper. They found, through the application of theory and a limited amount of data, that variations in sheet modulus are caused mainly be variations in fiber modulus rather than by changes in sheet structure (i.e., bonding).

**Compressive Strength and Elastic Properties.** There is strong theoretical evidence linking compressive failure to elastic properties. Peterson (52) developed a unified container performance and failure theory from first principles using orthotropic stress-strain relations for liner and corrugating medium. The development of a theoretical relationship between compressive strength and elastic sheet properties is described in a paper by Habeger and Whitsitt (12). The conceptual model takes into account the heterogeneous layered structure of paper. It assumes that failure occurs due to buckling of one of the fiber layers that comprise the substructure of the sheet. The buckling deformation of the fibrous layer results in shear and transverse deformations in the adjacent media. Therefore, the load at failure depends on the in-plane modulus of the layer and the out-of-plane moduli. Research carried out at IPC/IPST has experimentally indicated the accuracy of the theoretical relationships (10).

Relationships between compressive strength and elastic properties can take several forms. Empirical relationships between the shear and Young's moduli are often useful in working with elastic properties. By making use of such relations, compressive strength can be expressed in terms of two elastic stiffness rather than three. In addition, the form of the relationship with $E_x$ or $E_y$ and $E_z$ is often the most useful because there are often advantages to measuring $E_z$ rather than shear moduli by acoustic means.

The expressions for relationships between MD and CD edgewise compressive strength, measured with the STFI tester and measured as Ring Crush, are given later when the modeling of these properties is discussed. Relationships between STFI compressive strength and elastic stiffness for medium and liner are shown in Fig. 4.

Both the STFI compressive strength and Ring Crush depend on the elastic stiffness in the direction of load and the out-of-plane stiffness. The Ring Crush test is inherently a more complex test than the STFI test. Because of the fixed ring size and height, there are differences in the mode of failure between thin and thick materials.

As explained above, the fiber elastic modulus determines the maximum achievable sheet elastic modulus. Consequently, there is a relationship between sheet compressive strength and fiber modulus. This relationship, shown in Fig. 6, illustrates the connection between fiber properties and compressive strength.

**Stiffness and Thickness.** The dominating conditions for compression failure are shear and bending failure. The bending resistance of paperboard depends on sheet stiffness. Board stiffness and the stiffness of individual fibers are determined by their respective elastic moduli. Stiffness, D, of a homogenous sheet is equal to the product of the modulus of elasticity, E, and the moment of inertia, I,

$$D = E\,I \qquad (1)$$

The value for I in a homogenous sheet of thickness and basis weight b is given by

$$I = \frac{bt^3}{12} \qquad (2)$$

The stiffness of a multi-ply sheet is represented by the weighted average over all plies.

$$D = E_1 I_1 + E_2 I_2 + .... + E_n I_n \quad (3)$$

The subscripts in the formula refer to the individual plies. The strong effect of sheet thickness on stiffness and thus on compressive strength is obvious from the equations. For multi-ply sheets an additional important variable is the distance of the fiber layer from the center of gravity. The contribution of the fiber layer to sheet stiffness is higher the further away from the center of the sheet it is located. In the manufacture of two-ply linerboard, this aspect is important for the z-directional structure of each ply. The practical application of this would be the usage of stock with high modulus of elasticity near the surfaces of the board. Virgin fiber can be used in the outside plies and cheaper stock in the middle to separate the outer plies thus increasing its moment of inertia. Improvements in linerboard compressive strength have been achieved using a three-ply structure (28).

For maximum compressive strength, linerboard should have fibrillated and well-bonded fibers, especially on both surfaces, high bulk, and good ply-bond between the top and base sheets (1).

Assuming that Taber stiffness is actually the flexural resistance of the sample expressed in metric units, it is possible to define the stiffness, D, or the flexural rigidity, directly in terms of the Taber stiffness tester reading using the instrument sample dimensions and a correction factor for sheet density. A simplified formula giving an approximation of the relationship is

$$T = 638 D \text{ (g/cm)} \quad (4)$$

where D is in units of lb in (28).

**Caliper.** Many papermaking variables that affect modulus of elasticity also affect sheet thickness. For instance, increased pressing improves modulus but reduces thickness. The effect of certain papermaking variables on compressive strength is therefore not straightforward but depends on the relative effect of different factors.

In most cases the modulus of elasticity, sheet thickness, and the location of fiber layers can be used to explain the effects of papermaking variables on the edgewise compressive strength. This approach is also used in MAPPS where compressive strength is predicted based on elastic stiffness, the products of modulus, and board thickness. The importance of thickness to compressive strength can be seen from Fig. 7.

**Formation.** Formation, the degree of uniformity of the fiber distribution in a sheet of paper, is an important factor influencing both tensile and compressive strength. In a sheet with poor mass distribution, the stress is not evenly distributed. Therefore, failure is initiated at areas of low mass. The effect of formation on paper properties, particularly strength, is more apparent at lower basis weights.

Sheet formation is controlled by the degree of fiber dispersion or alternatively the floc size in the discharge from the headbox. In addition to the hydrodynamic conditions of the machine, flocculation is affected by fiber properties, such as length, flexibility, fibrillation, and surface charge. Wet-end additives also affect flocculation. The main factor, however, which affects flocculation is the headbox consistency. Since linerboard is made from long fibered pulps at relatively high consistencies, the tendency of the stock to flocculate is high. Sozynski and Seth (6) have tested the extent to which the deficiency in the compressive strength of commercial linerboards can be attributed to sheet formation. The formation index shown in Fig. 8 was measured with the M/K formation tester. The higher the index, the better the sheet formation. The decrease in compressive strength is plotted against the formation index of commercial linerboard sheets. These tests indicate that formation is in part responsible for the compressive strength deficiency (6).

**Fiber Orientation/In-plane.** Much of the effect of wet-end variables on edgewise compressive strength can be explained by changes in fiber orientation which affect sheet directionality or anisotropy. When webs are formed at low consistency, fibers are oriented mainly in the plane of the sheet. The extent of in-plane anisotropy can be measured in a number of ways. The MD/CD breaking length (tensile strength) ratio is often used. The relationship between fiber orientation ratio (tensile ratio) and compressive strength in different directions is shown in Fig. 9

Increasing fiber orientation influences MD and CD compressive strength differently. As fibers become more oriented in the machine direction, strength properties increase in that direction and decrease in the CD both in tension and compression. Since the CD compressive strength is more important for linerboard, (though good MD properties are also needed for some performance aspects) the squarest possible sheet and minimum amount of orientation is desired.

If the compressive and tensile strengths in MD and CD are compared, the sheet becomes less anisotropic in compression than in tension (14). Based on the relationships found between the elastic constants and compressive strength in paper, it is possible to show that for an MD/CD tensile ratio, R, the MD/CD compressive strength ratio is given by $R^{0.75}$.

It should also be noted that there can be a significant z-direction variation of in-plane fiber orientation. This may be caused by the type of former, its drainage devices, and the development of the boundary layer between slurry and drained mat. This variation can lead to property variations from one plane to another in the sheet (1, 29).

**Fiber Orientation/Out-of-plane.** A certain amount of out-of-plane or z-directional fiber orientation tends to be beneficial for compressive strength. The more felted structure provides increased stability against compression failure and leads to favorable stress distribution in the sheet. The more the fibers are oriented in the z-direction, the bulkier the sheet tends to be and the higher the compressive strength (1, 9, 14). High consistency forming methods tend to increase z-directional fiber orientation. The achieved out-of-plane orientation usually results in a loss of in-plane strength properties but is balanced by a gain in out-of-plane related properties. The high consistency-formed sheet in which the fibers are oriented to some extent in the thickness direction has a dramatically higher Scott Bond value and the thickness and the bending stiffness are also markedly increased. The compressive strength also increases slightly (14).

Past work at the Institute has shown that compressive strength increases rapidly with increasing z-direction bond strength up to a certain level of bonding at which point the increase is less pronounced. Among other things high consistency forming has been shown to produce large increases in internal bond strength (4, 8, 9).

Grundstrom and co-workers (30) have compared the properties of conventional and high consistency formed medium. The greater z-direction fiber orientation of the high consistency-formed medium resulted in increased compressive strength and Scott Bond, while burst and tensile strength decreased by about 33%.

**Sheet Cleanliness.** Poor washing and screening of pulp also tend to reduce sheet strength. Shives, bark, dirt particles, and residuals in pulp bond poorly thus reducing fiber-to-fiber bonding. In addition, these particles act as points for stress concentration which may lead to premature failure of the sheet. Linerboard furnishes with high secondary fiber content can contain substantial amounts of shives, bark, and dirt.

Sozynski and Seth have demonstrated that compressive strength can be improved 25-30% with improved screening, while tensile strength is improved by only 10-15%. The larger the size of the shives, the greater the loss in compressive and tensile strength properties (6).

**Effect of Raw Materials**

- Wood species
- Fiber characteristics
- Pulping method, recycling
- Yield
- Chemicals and additives

As mentioned above, the compressive strength depends on inter-fiber bonding. However, as a limiting bonding level is reached, the compressive strength of the sheet is controlled by the compressive strength of the individual fibers. Based on this assumption and the theory of Cox, it is possible to show that the compressive strength (and modulus) of paper should be one-third of the axial compressive strength (and modulus) of the individual fibers. Thus, for high sheet compressive strength the fibers should have a high bonding capability as well as a high fiber modulus and compressive strength.

**Wood Species.** According to experiments made by Seth, Sozynski, and Page (5), increasing the bonding of sheets by wet pressing or beating increases edgewise compressive strength to a plateau that is nearly one-third of the compressive strength of single fibers but falls somewhat short of that. The plateau appears to be a function of wood species (i.e., fiber characteristics). Wood species or fiber type determines the basic properties of fibers including its stiffness and bonding characteristics. Low density slow growing northern conifers give better compressive strength than southern softwoods. Among North American softwoods, the strengths reached by Douglas fir and loblolly pine are the lowest. The compressive strengths reached by hardwoods are generally as high as those reached by softwoods. In Fig. 10, compressive strength vs. wet pressing for sheets made of similar unbleached kraft pulps of various species are compared. These experiments indicate that hardwoods can be used to replace softwoods without serious loss in compressive strength, while softwoods are needed to optimize other properties.

**Fiber Characteristics.** The above-mentioned authors have also determined relationships between fiber properties and compressive strength (5). Using pulps of different fiber length distributions, experiments showed that a reduction in average fiber length from 2.1 mm to 1.25 mm reduced tensile strength by 22% but reduced compressive strength by only 8%. It is also shown that compressive strengths for hardwoods (which have on-average much shorter fibers) are very similar to those for softwoods.

Fiber characteristics which do appear to affect compressive strength are fiber chemical composition, fiber-wall thickness, fiber coarseness, and fibril angle. The reason these factors are influential is its strong relationship to single fiber modulus.

High hemicellulose content is advantageous to compressive strength because it improves bonding properties. Hemicelluloses favor bonding in two ways. By contributing plasticity to the fiber wall, fibers are able to conform more easily during forming and pressing. Also the more mobile hemicelluloses contribute more hydrogen bonding per unit area than do the cellulose surfaces. The effects of hemicellulose content is also interrelated with fibrillation and with fines developed in beating. There is, however, an upper limit to desired hemicellulose content. Pulp containing too much hemicellulose hydrates too rapidly and loses freeness before adequate strength is developed in refining. There is an optimum value for hemicellulose content that depends on the sheet properties that are desired. Greatest overall strength is attainable with about 18% hemicellulose content. There is also a optimum lignin content for maximum strength. Pulps with too high lignin content are slow beating and show poor interfiber bonding. Stiffness is, however, increased by the presence of lignin and certain strength properties have their highest value with about 5% lignin content (25).

Fiber bonding is governed essentially by the degree of plasticity developed in the wet fibers. A very good correlation was found between the sheet compressive strength and fiber cell wall thickness (5).

The fibril angle, the angle between the fiber axis and the fibrils in the cell wall is a major factor controlling the longitudinal modulus of wood. The modulus falls with increasing fibril angle. Since the fiber modulus is a major contributor to the sheet modulus and therefore the compressive strength, fibril angle is also expected to influence compressive properties. Page et al. have shown that the elastic modulus of pulp fibers of softwoods in the most common range of fibril angles, 0 to 20, is about 4.5 to 5.5 GPa. This relationship is surprisingly independent of the pulping process and yield in the yield range generally used. The relationship between elastic modulus and fibril angle is presented in Fig. 11. The relationship between compressive strength and single fiber modulus is shown in Fig. 6 (26).

Increasing single fiber stiffness tends to reduce sheet compressive strength because the less flexible fibers bond poorly, and bonding is also an important factor determining sheet compressive strength. Fiber flexibility decreases with increasing yield. Refining increases wet fiber flexibility. Wire retention yields a good correlation with fiber flexibility because the more flexible fibers tend to pass through the forming screen (29). Meyer and Wahren found a direct proportionality between the shear modulus of the network and the stiffness of the individual fibers (57). This finding was then corroborated by Bergman and Takamura (55) and later by Frolander and Hartler (56).

In summary, for maximum compressive strength, the wood source should contain thin-walled fibers of low fibril angle with good bonding properties. The fiber length distribution is not necessarily a major concern. The deviations in compressive strength between the different wood species were found to correlate well with the deviations in fiber-wall thickness and fibril angle (5).

**Pulping Method, Recycling.** Various furnishes differ in its compressive and tensile potential. Results by de Ruovo et al. (31) show that NSSC hardwoods and recycled corrugate have relatively low tensile strength but good compressive potentials.

One of the most significant fiber properties affected by recycling is internal fiber bonding. Beating causes internal delamination and opening up of the structure of the fiber walls. The drying of paper partially reverses this process. During drying the opened structure shrinks and internal bonding takes place within the fiber itself. This bonding does not disintegrate upon rewetting. New beating can restore the opened structure only to a degree.

Recycling tends to reduce fiber length, increase fiber fragmentation, increase fiber stiffness, and decrease flexibility and conformability (4, 31). The decrease in fiber swellability upon drying is sometimes considered to cause many of the adverse effects of recycling. In terms of paper properties, recycling tends to reduce fiber bonding as a result of the decrease in fiber flexibility and conformability. Reduced bonding results in a decrease in tensile and certain other strength properties, an increase in stiffness, and only a moderate decrease in compressive strength. (25) . Lindstrom and Carlsson ( 62 ) found that the pH and the ionic form of the carboxyl groups on the pulp fibers during drying influences the closure and collapse of fibers in the drying step and the subsequent loss of water retention values and plasticity during rewetting.

**Yield.** The effect of pulping variables on compressive strength are generally considered to be beyond the scope of this review. Pulping yield is discussed in relation to raw material utilization and its importance to mill economics.

For unbleached pulps at high yields where there is lignin still remaining on the fiber surface, the bond strength is governed by the character of lignin. Kraft lignin with its low hydrogen-bonding capacity causes a low bond strength between the fibers, while sulfite lignin with its sulfonic acid groups contributes to relatively high bond strength between the fibers. At lower yields, when the surface lignin is dissolved, the bond strength is governed by the presence of low-molecular-weight carbohydrates on the surface. The gradual dissolution of hemicelluloses during pulping causes bond strength to decrease (25). This would indicate that as yield decreases, sheet strength would also decrease. However, the opposite is usually the case. The difference is usually attributed to the increase in fiber conformability and relative bonded areas with decreasing yield. The net effect is generally an increase in apparent sheet strength with decreasing yield to a point at which fiber tensile itself begins to decrease significantly. These concepts may not apply to elastic and compressive properties, however. For example, relative bonded area may play a much more significant role than bond strength in compressive failure than in tensile failure. For example, if the sheet is pressed to the same final density, the effect of yield has been shown to nearly disappear.

Fig. 13 shows the effect of beating and wet pressing on compressive strength of paperboard made from kraft pulps of different yields. Compressive strength increases with increasing wet pressing. At a given density the strength achieved decreases with increasing yield.

Fellers (14) has shown that whereas tensile strength is governed primarily by the cellulose content of fibers, compressive strength is almost independent of yield, implying that both cellulose and lignin are load-bearing components in compression. Others have drawn simular conclusions (5). The relative importance of these different cell-wall components for the load-bearing capacity of paperboard in compression and in tension has been studied. The hemicellulose content was kept fairly constant in these experiments thus making it possible to compare the influence of only lignin and cellulose. Also, density was kept constant in the experiments.

The experiments showed that the compressive strength is relatively constant over a softwood kraft pulping yield range from 47 to 66% at constant density and hemicellulose content. A shallow maximum can be seen at about 53% yield. Tensile and compressive strengths are clearly affected differently by yield. The results of the experiments are shown in Fig. 14a. The role of lignin is further illustrated in Fig. 14b which shows that the strain-to-failure in compression is virtually independent of yield, while in tension it is lower at higher yields. Lignin thus appears to act as a brittle component in tensile loading but has no negative effect on the strain in compression (14). These findings are in agreement with the work of Shick and Snow, who studied high yield sulfite pulping of southern pine (33). The practical consequence of this is that acceptable compressive strengths can be achieved with higher yield pulps provided sheet density is maintained.

**Chemicals and Additives.** The addition of almost any nonfibrous substance to the fibrous furnish tends to reduce interfiber bonding. This is especially true for hydrophobic substances such as rosin or paraffin, which result in a very great decrease in strength. It is also true to a lesser extent for some of the hydrophilic materials, such as clay and alumina. The loss in strength which occurs when paper is sized with rosin is well recognized. Too much antifoam added at the paper machine may also reduce interfiber bonding. Alum has a very decided effect on sheet strength since it reacts with alkali in the water to form alumina floc, which has a harmful effect on fiber bonding.

A few substances increase the strength of the sheet when included in the fiber furnish. These belong to the class of high-molecular-weight hydrophilic colloids of which starch, proteins, cellulose derivatives, vegetable gums, and water-soluble resins are examples. These materials act by being absorbed on the fiber surface where they hold the sheet together through a fiber-to-fiber bond (25).

Excessive use of internal sizing, such as rosin or alum reduce compressive strength and elastic modulus by reducing the internal bond strength of the sheet. These are referred to as debonding agents. When added in small amounts of up to 1.0%, compressive strength and modulus may not be affected appreciably.

Compressive strength can be improved substantially by using certain wet-end additives or by the application of size. Some wet-end additives improve bonding and sheet stiffness. Size application is especially effective because it increases bonding on the surfaces which contribute most to compressive strength (1).

**Effect of Papermaking Variables**

Paper manufacturing variables which affect basic sheet characteristics discussed above will also change the board compressive strength. The following papermaking operations will be discussed:

- Screening
- Refining
- Forming
- Wet pressing
- Drying
- Calendering

**Screening.** Linerboard furnishes should be screened and cleaned thoroughly to minimize loss in the sheet strength. Screening and cleaning operations are designed to remove particles, such as shives, bark, and dirt which contribute to sheet breaks on the machine or degrade optical properties. To maintain aesthetic quality and machine runnability, these defects are seldom tolerated in fine papers, although its presence in paperboard sometimes is ignored. They can, however, act as points of stress concentration and lead to failure.

The relationship between stock screening and compressive strength properties, shown in Fig. 15, indicates that both compressive and tensile strength decrease with increasing shive size (6).

**Refining.** Compressive strength is primarily affected by factors influencing density (fiber bonding), such as wet pressing and refining. Refining is perhaps the most widely used means of controlling the bonding capability of fibers and is, therefore, considered the most important part of the stock preparation system. Refining influences bonding through the structural modification of pulp fibers. Determining what changes are responsible for certain paper properties is difficult since many of them are not readily detectable in the dry state. Refining brings about the following changes in fiber structure:

- Internal fibrillation associated with increasing fiber flexibility.
- External fibrillation associated with increasing fiber surface area.
- Microcompressions, kinks, curls associated with changing fiber deformation potential.
- Rupture, cutting associated with changing fiber length distribution.

- Fines generation associated with increasing drainage assistance.
- Dissolution of cell-wall material.

Internal fibrillation refers to the progressive delamination of the cell wall. This change is accompanied by an increase in wet fiber flexibility and increased swelling (i.e., moisture uptake) due to greater accessibility of hydrophilic surfaces. Increased fiber flexibility is perhaps the most important factor controlling the establishment of interfiber bonding for chemical pulps.

During the course of refining, the primary wall and the outer secondary wall of the fiber may be partially removed. The material which is completely removed and further reduced in size contributes to the fines content of pulp. Material which remains attached to the fiber in the form of membranes or fibril networks is referred to as external fibrillation. This material contributes to a significant increase in fiber surface area. External fibrillation may reduce the fiber tensile strength and modulus. However, the net effect of sheet strength is overwhelmingly positive due to increased bonding potential through the Campbell effect and through the exposure of potentially better bond sites.

Microcompressions, kinks, and curls may be introduced or eliminated by refining. Page (34) has attempted to quantify the increase in the number of microcompressions in the cell wall with an increase in refining consistency. Pulps refined at high consistency (10-40%) have more kinked and curled fibers than fibers refined at low consistency (3-6 %). Page (13) has also shown that the deformation potential of the fiber is changed, resulting in an increase in strain under stress and a decrease in modulus by the introduction of kinks and curls in the fibers. Introducing curl into otherwise straight fibers reduces sheet modulus. In addition to the effect on fiber and sheet modulus, kinks, curls, and microcompressions have a profound effect on paper formation. This creates an additional indirect effect on strength.

Refining shifts the fiber length distribution by reducing the mean and generally reducing the standard deviation of the distribution. This change in fiber length may be the result of "cutting" (shear failure) but is more likely to result from fiber tensile failure. The change in fiber length distribution will be strongly dependent on the pulping process used. Sulfite fibers undergo a greater change in fiber length distribution than kraft fibers. In general, we would prefer to minimize fiber length reduction in order to maintain sheet strength, although a reduced fiber length may lead to improved formation which tends to improve strength. Fines generation is a consequence of most refiners. Fines have a high surface area which reduces drainage and water removal but improves fiber bonding and strength.

The two effective variables of refining are amount of refining and nature of refining performance. The amount of refining determines how far pulp properties are developed and is measured by specific energy consumption. The amount of refining can be adjusted by changing the motor load. The nature of refining performance determines the rate at which the different pulp properties develop and is measured by specific edge load.

Low specific edge load means that refining energy is applied with a high number of low-intensity "impulses." High specific edge load produces harder impulses on the fibers at lower frequency. Refiner plate patterns with finer bars, that is, closer bar spacings with the same bar width, produce lower specific edge load.

Fig. 16 shows that Ring Crush compressive strength improves rapidly and linearly with increased refining. This is due to the increased fiber bonding and, at low refining consistency, to reduced fiber curl. Refining low-yield pulps at lower edge load, i.e., 0.41 Hsp s/ft lead to a higher strength than the use of a higher edge load at the same total refining power. When pulping yield increases, the situation changes and high specific edge load, 1.23 Hsp s/ft, gives better Ring Crush. At high pulp yield fibers are stiffer and more covered with lignin requiring harsher mechanical treatment to develop elastic properties for compressive strength (1).

**Forming.** During the forming process a fiber network is established. Forming is, of course, the first stage of of water removal. The type of forming process will determine the type of network produced, which will have a significant impact on paper properties, particularly the balance between in-plane and out-of-plane properties. Forming changes the network in the following ways:

- Formation, small scale basis weight distribution.
- Fiber orientation in-plane and out-of-plane.
- Z-directional anisotropy, fines and fiber distribution.

The sheet forming process on a fourdrinier wire involves effects, such as drainage, generation and decay of turbulence, formation and breakdown of fiber networks, retention and transport of fine particles in the mat, compaction of the mat, and shear forces between the mat and free suspension. Conceptually, forming is a composite of three basic hydrodynamic processes: drainage, oriented shear, and turbulence. All these processes occur simultaneously and are not wholly independent of each other.

The most important effect of the drainage process is the dewatering of the fiber suspension to form the mat. When the fibers are free to move independently of one another, drainage proceeds by the mechanism of filtration and the fibers are deposited in discrete layers. Filtration is the dominant mechanism in most fourdrinier forming applications as shown by the layered structure and relatively uniform formation of the sheets. When the fibers in suspension are immobilized, they floc together in coherent networks; drainage then occurs by thickening resulting in a more felted and flocky sheet structure.

Papermaking suspensions spontaneously form networks during drainage unless either sufficient dilution is used or supplemental mixing energy (e.g., turbulence) is provided. Dilution is a powerful mechanism for dispersion, but the level required to adequately control flocking on paper machines is not economically feasible. Additional dispersion must be generated during drainage by the use of turbulence-inducing drainage elements below the forming wire or by shear-inducing devices above the wire. In each design, however, the three elementary forming effects of dilution, turbulence, and oriented shear are applied to different degrees in an attempt to optimize the sheet quality.

**Formation.** Sheet formation is controlled by the dispersion or flocculation of the stock. In addition to the paper machine's hydrodynamic conditions, flocculation is affected by fiber properties, such as length, flexibility, fibrillation, and surface charge. Wet-end additives also influence flocculation.
The main factor that affects flocculation is headbox consistency. Since commercial linerboards are made from long-fibered pulps at relatively high consistencies, the tendency of the stock to flocculate is high. Therefore, the effect of formation can be severe and the consequent loss in strength can be considerable. At high dilution, i.e., low consistency, dewatering occurs by filtration, and flocculation is minimized. In top-wire or twin-wire formers, drainage occurs in both directions thus increasing shear and improving sheet formation.

The effect of stock consistency on handsheet formation and consequently elastic modulus and compressive strength is shown in Fig. 17. In experiments by Sozynski and Seth (6), beta-radiographs were used to determine the mass distribution in handsheets made at different forming consistencies. Results clearly indicate that as consistency of the stock during sheetmaking is increased the sheet strength drops considerably. For example, increasing stock consistency from 0.05 to 0.5% reduces compressive strength, and elastic modulus dropped by 26% and 18%. The effect of sheet formation on tensile strength is even stronger. Tensile strength dropped by 47%.

High consistency forming methods are used in order to increase fiber orientation in the thickness direction. This effect is discussed in more detail in connection with fiber orientation. In these methods the formation has to be controlled by other means.

**Fiber Orientation.** Orientation within the plane of the sheet is controlled by the jet-to-wire velocity difference. If the wire velocity is higher than jet velocity, the PM is "dragged," and more fibers are oriented in MD direction. Fibers are also strongly oriented if the machine is "rushed," i.e., the jet velocity is higher than wire speed. As the jet-to-wire speed differential approaches zero, the fiber orientation becomes more random, resulting in a more "square" sheet.

Higher headbox consistency generally produces sheets with less in-plane orientation. At high consistency, fibers tend to resist aligning forces in the jet and on the wire. Both wet pressing and drying restraint can further affect sheet anisotropy. The effects of drying strain are discussed later in more detail. Refining also affects fiber orientation indirectly through its effect on fiber length and freeness.

The use of new high consistency forming methods (in the 2-6% range), such as foams to reduce surface tension, can significantly increase out-of-plane orientation. Instead of the conventional layered structure, sheets are produced with fibers arranged as a three-dimensional network, resulting in some out-of-plane orientation. These sheets have dramatically higher Scott Bond, caliper, and bending stiffness. Compressive strength also increases slightly due to increased resistance of the felted structure to compressive failure (14). Increased z-direction orientation increases caliper and reduces density. The more the fibers are oriented in the z-direction, the bulkier the final sheet tends to be and the higher is the compressive strength.

Z-direction fiber orientation is also affected by rush drag conditions. Rush conditions may favor the alignment of fibers in the z-direction (1). High drainage rate also tends to increase fiber orientation in the z-direction.

**Z-Directional Anisotropy.** As mentioned above, there can be variation of in-plane fiber orientation caused partly by drainage devices. The distribution of fines in the thickness direction of the sheet has some effect on compressive properties. Fines contribute to fiber bonding. Thus a uniform distribution of fines leads to more uniform bonding throughout the sheet. For optimum compressive strength both outer surfaces of the board should be well bonded. For instance table rolls typically cause the fine material to be washed from the wire side resulting in a less-bonded bottom surface. Twin-wire units improve compressive strength through more uniform fines distribution and more symmetrical outer layers.

Drainage and turbulence on the wire after the secondary headbox are important for the ply bond of the liner layers. Improved ply bond leads to improved compressive strength. Moderate turbulence is probably advantageous because it intermingles fibers in different layers thus improving the ply bond.

**Wet Pressing.** Pressing increases sheet density and affects fiber bonding. When the fibers come closer to each other in a wet state, the conditions for fiber bonding improve. On the other hand, increased density (reduced caliper) reduces sheet stiffness. This negative effect on compressive strength is, however, offset by the improved bonding in the sheet. Thus, the overall effect of pressing is positive. In practical terms, increasing the press load or dwell time improves compressive strength.

Wet pressing is basically a process of water removal and web consolidation. During wet pressing, the network is consolidated or densified by the action of external mechanical and internal capillary forces (Campbell's forces). The extent of consolidation depends on the following variables (29):

- Moisture content of the sheet
- Basis weight
- Speed
- Felt type and configuration (single or double)
- Press load (roll hardness) and configuration (number of presses, extended nip)
- Furnish and refining level
- Roll temperature

The sheet dryness after the press increases with increased freeness, sheet temperature, time in the nip, and average nip pressure. As a rule of thumb, burst, compressive and tensile strength, and sheet density increase 10-20% as the sheet dryness out of the press increases. A further benefit is a reduction in drying energy. The apparent density of the dry sheet increases with increasing water removal. The higher density obtained increases compressive strength and Young's modulus.

Fig. 19 shows the improvement in compressive properties seen by Justus and Cronin (22) through increased dryness out of the press.

Improved pressing through so-called "press drying" can be achieved in a variety of ways. One approach uses extended nips to increase time at the nip and press impulse tenfold. Steam boxes may raise temperatures to 80 to 90°C, leading to dryness improvements of 5-10%. Anderson and Back showed an increase in final dryness by increasing press temperature. It is believed that bonding is influenced by the flow of the hemicelluloses under heat and pressure. However, work at the Institute (9) has shown that cold (room temperature) press-dried sheets exhibit compressive strength in the same range as hot-press dried sheets at equivalent densities. The lignin and hemicelluloses apparently can flow and produce high fiber bonding even at room temperature.

Stiff hardwood fibers can be pressed to high densities to obtain relatively high compressive strengths and other properties (9).

By increasing the number of press sections or nips, it is possible to increase overall water removal and sheet density. During pressing, fine material inside the sheet migrates toward the side where the water is removed, i.e., the felt side. The sheet is also compressed more on the felt side. Clearly symmetrical water removal through used double-felted nips is beneficial to compressive strength since the density profile and fines distribution are both more symmetrical.

**Drying.** Draw and shrinkage control of a paper web during drying can have a profound effect on paper properties. Unless restrained during drying, a web will undergo significant shrinkage. This results from the lateral shrinkage of one fiber being directly transmitted to the fiber to which it is bonded. The lateral shrinkage of fibers will depend on its morphology and level of refining. The shrinkage of the network will also depend on interfiber bonding and fiber orientation.

Page, Seth, and De Grace (13) have examined sheets from dried unbeaten and beaten pulps that had been pressed to identical scattering coefficients. Although the sheets had similar degrees of bonding, the beaten sheets had much higher elastic moduli. The scanning electron micrographs of the specimen showed that the fibers in the unbeaten sheets were clearly more crimped and kinked than those in the beaten sheets. The rational was that during drying, the highly swollen fibers shrink, resulting in the transfer of transverse shrinkage stresses from one fiber to another. Thus, microcompressions are induced in the crossing or bonding points of the fiber network. This produces tension in the unbonded regions of the fibers, which causes tightening of the sheet structure. This tension can remove the out-of-plane curl and crimps in the fibers, leaving them ready to take further stress. When the crimps are at least partly removed, the elastic modulus of the sheet increases. This only occurs, however, if the sheet is restrained from shrinkage. If shrinkage is allowed, no such tightening of the structure is permitted and the modulus is low. In Fellers (14) view, drying restraint activates the fiber structure and diminishes the number of dislocations, resulting in fewer defects and higher strength. Thus, variables affecting compressive strength during drying are the degree of sheet shrinkage or stretch. If the sheet is allowed to shrink, its elongation increases, and the modulus of elasticity and compressive strength decreases. If shrinkage is prevented, that is, the sheet is stretched during drying, the modulus of elasticity and compressive strength increases. The effect of shrinkage on the stress-strain curve and modulus of elasticity is shown in Fig. 20.

Another interesting finding is the effect of draw and shrinkage control on the apparent density of the sheet. Experiments at the Institute (29) have shown that the density of freely dried sheets is greater than sheets dried under full restraint. Wet straining followed by complete restraint during drying reduces sheet density. The variation of sheet density with drying restraint varies as shown in Fig. 21. In this case, the increase in compressive strength is not accompanied by an increase in density, which normally is the case.

Since fibers in machine-made paper are usually more oriented in the machine direction than in the cross direction, the web tends to shrink more in the cross direction, and modulus of elasticity and compressive strength are usually lower in cross direction than in machine direction. Fellers (14) examined the effect of drying restraint on sheets of different degrees of fiber orientation. Fig. 22 shows the strain-to-failure vs. fiber orientation for sheets dried under different conditions.

For freely dried sheets, the strain-to-failure in tension increases in the CD and decreases in the MD with increasing degree of fiber orientation. If the sheet is restrained during drying, both MD and CD strain-to-failure are the same and independent of fiber orientation with lower values with free drying.

The strain-to-failure in compression also increases in the CD and decreases in the MD with increasing degree of fiber orientation. Contrary to the behavior in tensile test, the general pattern is the same for the sheets dried under restraint, although the strain-to-failure has lower absolute values. If the strain-to-failure increases, the modulus of elasticity decreases, resulting in a reduction in compressive strength.

High drying temperature favors the generation of drying stresses in the sheet and would therefore be favorable to compressive strength. The effect of drying rate and temperature on paper properties is greater for high basis weight papers because of the viscoelastic nature of fibers.

**Calendering.** Dry pressing decreases caliper and increases sheet density. Because these effects occur in a dry state, bonding of fibers does not improve. Calendering normally results in decreased stiffness and compressive strength.

Sozynski and Seth (6) show in Fig. 23 that tensile strength appears to increase slightly with light calendering but drops with further calendering. The compressive strength and elastic modulus drop at each stage of calendering. In the experiments, the sheets were calendered at 50°C through four successive nips with increasing load. The cumulative effect of the nips is presented as a function of the last nip load. Obviously, excessive calendering of the sheet should be avoided. It should be noted that calendering does not have an appreciable effect on the internal bond strength of the sheet.

## SIMULATION OF THE COMPRESSIVE STRENGTH

The simulation of the linerboard compressive strength is done using the MAPPS modular process simulator developed by the Institute of Paper Science and Technology. MAPPS is a sequential, modular simulator which can be used to simulate virtually any papermaking process in either a steady state or dynamic mode. MAPPS currently contains approximately 100 process and utility modules. Each process module models a particular unit operation. Developing a MAPPS simulation model requires that the complex process be simplified into a series of unit operations. The second step involves selecting the appropriate MAPPS modules from the library to represent each unit operation.

The next step is to build a flowsheet model by connecting the unit operations with the appropriate process streams. The MAPPS streams represent physical process flows or information flows between the modules. In addition to the mass and energy simulation, MAPPS is also capable of predicting end product properties and its development throughout the process. The simulation of properties, referred to as the Performance Attribute System, is of particular interest in this work with primary focus placed on the production of board compressive strength.

### Performance Attribute System

**Performance Attribute Streams.** The Performance Attribute system in MAPPS uses a variety of nonconserved properties and characteristics, that is, quality information about the fibers through the process. Performance attributes, PATs, are carried by Performance Attribute Streams, PAT-streams, that exist parallel to normal process streams which carry the mass and energy flows (45). Like the regular process streams, the PAT-streams transfer information from one module to another. The modules of the simulation recognize the PAT data and process algorithms that use and update PATs. Almost all MAPPS modules work with PAT data, except those modules that do not deal with fiber streams.

PAT-streams are defined and handled in much the same way as the regular process streams. For more information about the individual algorithms used by MAPPS to calculate the various PAS-stream properties, please refer to the MAPPS Programmer's guide.

PAT-streams contain 28 attributes that characterize individual fibers or the developing fiber network. Attributes related to fibers characterize fiber composition, shape, or physical properties. Attributes related to the network characterize fiber bonding and anisotropy of the paper. In addition, paper fillers are characterized, but filler attributes are irrelevant in unbleached linerboard and are not considered in this study. The fiber and network property development and the effects of papermaking processes can be tracked through the simulation by looking to PAT-streams and, in some cases, to calculated parameters of certain modules along the process.

The properties in the PAT-streams which influence linerboard compressive strength are listed in Table 1.

Table 1. Performance Attributes Related to Compressive Strength.

| Fiber composition: | MAPPS LABEL |
|---|---|
| Pulping yield on dry wood | YIELD |
| Kappa number | XKAPPA |
| Ratio of hemicellulose to total cellulose | FHEMI |
| Fiber shape: | |
| Weight average fiber length, mm | AVGL |
| Standard deviation of fiber length, mm | SIGL |
| Number average fiber width, mm | AVGW |
| Standard deviation of fiber width, mm | SIGW |
| Fiber length distribution type | IDIST |
| Cell-wall thickness, microns | CWTH |
| Fiber physical properties: | |
| Fiber tensile strength, km | FTENS |
| Fiber modulus, GPa | FMODU |
| Fiber stiffness factor | SMOD |
| Freeness (surface area), ml | CSF |
| Fiber network and bonds: | |
| Potential bonded area, top side | SB1 |

**Information Streams.** In addition to PAT-streams, in the case of multi-ply sheets, the multi-ply sheet structure information is passed through the flowsheet by means of the multi-ply information streams. The multi-ply information is established in the forming modules such as the fourdriner block (FOUR01) and modified in other modules such as the multi-ply former, MPFORM, the wet press, WPRESS, dryer, DRYER, or calender nip, CALENDER. As with streams, the multi-ply information streams carry only fiber and network characteristics relevant to each ply. The information streams are limited to three separate plies. The variables which are changed in the streams and multi-ply information streams are, of course, only those which are influenced by the current process block. In other words, each unit operation influences one or more PAT variables as described in the previous sections.

**Property Calculations.** Properties such as density, burst, tensile and compressive strength are calculated by the PROPS2 module which is designed specifically for multi-ply sheets. Handsheet and machine-paper properties of any fiber-containing stream are determined based on values from the multi-ply information stream and from the PAS-stream. In this study, the machine-paper properties are of primary interest. The compressive strength and the related properties of the final sheet studied are presented in Table 2. For single-ply sheets, the PROPS module is used to predict additional strength and optical properties.

Table 1. (continued) Performance Attributes

| Fiber Network and Bonds: | MAPPS |
|---|---|
| Symbol | |
| Potential bonded area, wire side | SB2 |
| Anisotropy: | |
| Formation coefficient, 0-1, 1=perfect | FORM |
| MD wet stretch in drying, % | WS |
| Fiber orientation | OR |

**Modeling of Compressive Strength**

The compressive properties in MAPPS are based on predicted elastic constants. The elastic constants are based on PATs which are changed by various unit operations.

Models for elastic moduli are based on data by Fleischman (27) and Berger (47). The elastic constants, $E_X$, $E_Y$, and $E_Z$ and the shear, $G_{XY}$, depend on effective bond density, $\rho_b^e$, and the following performance attributes: fiber modulus, fiber orientation, and wet strain. In general, as sheet density increases and formation improves, sheet moduli tend to increase, at least in the MD/CD plane. As fiber orientation and strain increase and the MD/CD ratio increases, $E_x$ increases and $E_y$ decreases. The model for compressive properties is visualized in Fig. 24.

**Model for Compressive Strength.** Failure compressive properties such as CD STFI and CD Ring Crush are functions of $E_x$ and $E_z$, or $E_y$ and $E_z$, respectively, based on relationships developed by Whitsitt from earlier work by Habeger [10].

$$\text{CD STFI (lb/in)} = 0.0341\,(E_x t)^{0.75}\,(E_z t)^{0.25} + 4.56 \qquad (4)$$

$$\text{CD Ring Crush} = 0.149\,(E_y t)^{0.75}\,(E_z t)^{0.25} + 0.062\,(E_x t)^{0.75}\,(E_z t)^{0.25} - 21.6 \qquad (5)$$

Abbreviations used refer to actual elastic constants and $E_x = C_{11}$, $E_y = C_{22}$, and $E_z = C_{33}$. t is the caliper of the sheet.

**Model for Elastic Constants.** Factors influencing the sheet elastic constants are the single fiber modulus, drying strain, fiber orientation, and effective bond density. Although the original data are based on only one species, the model introduces a species dependence by introducing the intrinsic fiber modulus and by the unique interactions between process conditions and species on bond density. The intrinsic fiber modulus in the original data is assumed to be 10 GPa.

It is interesting to note that bond density, an unmeasurable quantity, is used in the model rather than sheet density. The use of the bond density construct enables the model to account for effects such as formation, moisture and debonding agents, or debonding effects (i.e., densifying at calenders in dry state) which independently affect strength may not affect sheet density.

| Table 2. Tensile and Compressive Strength Properties Predicted by PROPS2. |
| --- |
| Basis weight, lb/1000 ft$^2$ (as is moisture content) |
| Sheet density, g/cc |
| Elongation, % |
| MD tensile strength, |
| CD tensile strength, |
| MD/CD tensile ratio |
| Caliper, mils |
| CD STFI, lb/in |
| CD Ring Crush, lb/in. |

The elastic moduli are given by

$$E_x = (E_f\rho/10\rho_b^e)\,(0.278 + 7.043\text{x}10^{-3}\,\rho_b^e + 6.513\,\rho_b^e\ \text{OR} + 1.904\,\rho_b^e\ \text{WS}) \qquad (6)$$

$$E_y = (E_f\rho/10\rho_b^e)\,(-0.8081 + 16.8\,\rho_b^e - 4.595\,\rho_b^e\ \text{OR} - .539\,\rho_b^e\ \text{WS}) \qquad (7)$$

$$E_z = (E_f\rho/10\rho_b^e)\,(0.30778 - 1.25\,\rho_b^{e\,2} + 1.1\text{x}10^{-2}\,\rho_b^e\ \text{OR} + 2.9\text{x}10^{-2}\,\rho_b^e\ \text{WS}) \qquad (8)$$

where $\rho$ is the apparent sheet density defined later.

**Factors Which Contribute to Elastic Modulus.** All intrinsic fiber attributes such as fiber modulus $E_f$ are initialized in the WOOD02 module based on a specified species. Selected attributes can be overridden in the WOOD02 block to modify the condition of the fibers to represent previous processing history. Fiber modulus is in the range of 4.5 - 5.5 GPa for softwood fibers with a typical fibril angle. Intrinsic fiber modulus defines the initial slope of the stress-strain curve and is thus a measure of the axial stiffness of the fiber.

Fiber elastic modulus is slightly reduced in refining in the pulp yield area relevant in this study. In the refiner, the fiber tensile and modulus is reduced by the ratio of the inlet over outlet freeness taken to a power which decreases with increased yield. For high yields, the power becomes negative, and fiber strength drops with increased refining. For pulping yields, less than 50% strength increases with refining.

Fiber orientation is represented by a performance attribute called the fiber orientation ratio (OR) defined as the cotangent of the average fiber orientation angle relative to the machine direction. For example, a value of 1 represents an average fiber orientation of 45 degrees or a random sheet, while a value of 1.5 represents a typical machine paper orientation, and a value of 2 represents a highly oriented sheet. Orientation coefficient must be specified in the forming step and is not currently predicted by the system.

The effect of wet straining the sheet near the end of the wire in the dryer section or in calenders also contributes to the sheet anisotropy. The effect of stretch is represented by the performance attribute parameter wetstretch (WS). Together the fiber orientation ratio and wet stretch influence the directional properties of the sheet. Wet stretch must be specified at each stage in which speed differentials occur or restraint is applied to the sheet such as at the end of the wire, between press nips, and in the dryer section.

The relationships between effective bond density ($\rho_e$) and papermaking conditions are shown in Fig. 25.

The detailed models describing all the effects considered in refining, forming, pressing, and drying modules are not presented here. For more detailed information, please refer to the MAPPS Module Technical and Programmer's guides.

The fiber surface area is represented by Canadian Standard Freeness, CSF or the hydrodynamic specific surface area, $S_h$. External fiber surface area is developed extensively by refining and is a critical step in papermaking. The fiber length distribution determines the fraction of fines and fibers in the pulp furnish. However, at any given fiber length, the degree of surface area development can vary. This is handled internally in MAPPS by the K-factor. Fiber surface area is a function of the fiber length distribution and the K-factor. The fiber length distribution is determined by the average fiber length, AVGL, and fiber length standard deviation, SIGL. The freeness, CSF, is directly related to the hydrodynamic specific surface area, $S_h$, through the following relation:

$$S_h = 95.7 - 0.012 \text{ CSF} \qquad (9)$$

The potential bonded area before wet pressing, $S_{bi}$, is proportional to $S_h$:

$$S_{bi} = S_c \, S_b \tag{10}$$

where $S_c$ represents the fraction of the total external surface area which bonds. $S_c$ decreases with increasing pulping yield, Y:

$$S_c = 0.0734 - 0.000654 \, Y \tag{11}$$

The result of wet pressing at pressure P is to increase $S_b$ from $S_h$ according to the following relationship suggested by Han:

$$S_b = S_{bi} \, (1 + M \, P^N) \tag{12}$$

where M and N are functions of CSF and Y given by:

$$M = e^{(0.14414 + 0.00127 \, CSF)} \tag{13}$$

$$N = 0.0003 \, CSF - 0.000015 \, Y \tag{14}$$

These functions show that compressibility decreases with decreasing yield and refining. However, this approach is further modified to account for the decreasing effect of multiple press nips by assuming a first order dependence of $S_b$ on pressure with an overall driving force which is equal to the difference between the total hydrodynamic specific surface, $S_h$, and the contact area entering the nip, $S_{bi}$.

Potential bonded area, $S_b$, represents the area in optical contact. On drying, hydrogen bonds are formed, and $S_b$ is converted to actual bonded area, $S_a$, according to the work of Nissan and Battan (48,49):

$$Sa = S_b e^{-(Xm - 0.075)} \tag{15}$$

where T is the temperature and $X_m$ the moisture.

One of the key concepts in the Performance Attribute model system is the relationship between potential bonded area, $S_b$, and apparent sheet density, r, and between actual bonded area, $S_a$, and bond density, $\rho_b$. Potential bonded area represents optical contact between fibers but does not necessarily mean that hydrogen bonds have been formed. A high level of optical contact leads to high sheet density. Conversion of optical contact surface into bonded surface leads to bond density and sheet strength. The actual bonded area formed in drying is assumed to be the average of both surfaces of the sheet; potential bonded area is represented by the values of two attributes $S_{b1}$ and $S_{b2}$ for the top and bottom of the sheet.

The models for sheet density and bond density have the same form. Sheet density depends on $S_b$, while bond density depends on $S_a$. For perfectly formed dry sheets, sheet density and bond density are the same. The density model was developed from the data of Alexander and Marton (50).

$$1/\rho = 1/\rho_u + [(1/\rho_l) - (1/\rho_u)](1/S_b^2) \quad (16)$$

$$1/\rho_b = 1/\rho_u + [(1/\rho_l) + (1/\rho_u)](1/S_a^2) \quad (17)$$

where $\rho_u$ and $\rho_l$ represent the upper and lower limits to the density which depend on freeness, CSF, cell-wall thickness, CWT, yield, Y, and fiber flexibility, SMOD or SF. These represent factors that influence fiber flexibility and bonding.

$$\rho_u = 1/(0.764 + 0.000477\ CSF + 0.1146\ CWT\ SF) \quad (18)$$

$$\rho_l = 1/[(1/\rho_u) + 43.14 + 0.08726\ Y - 0.05866\ CSF] \quad (19)$$

The concept of effective bond density is used to relate the independent influence of formation on bonding. If fibers are not uniformly distributed through the sheet, its network bonds will also not be uniformly distributed. There will be areas of high bond density and low bond density. Because the sheet tends to fail by sequence of small failures of weak points, sheet strength is determined primarily by the strength of weaker areas. Thus, the formation factor is defined in terms of the CV of mass density distribution. By taking the product of the formation factor and the bond density, the effective bond density is defined as a measure of the bond density of the weaker areas of the sheet. (23, 37, 38, 39).

$$FORM = 1 - CV/100 \quad (20)$$

$$\rho_b^e = \rho_b \text{ FORM } (1-f_{sus}X_{sus}) \tag{21}$$

Other factors which are accounted for in the bond density concept are the debonding effects of fillers which do not change bond strength or sheet density but inhibit fiber-fiber contact. As the solids are loading $X_{sus}$ increases, bond density decreases. The slope of the concentration-dependent term depends on shape factor $f_{sus}$. This is accounted for by the term $X_{sus}.f_{sus}$.

**Modeling Multi-ply Sheets.** For a single-ply process, the performance attribute streams contain sufficient information to define the properties and to simulate the effects of operations on the fibers and sheet throughout the process. However, for a multi-ply sheet, (in this case, two-ply sheet), the properties are determined by some average of the properties of the individual plies. Thus, it is essential that the intrinsic attributes of each ply be preserved. This is accomplished by passing an additional multi-ply information stream containing selected PAT values for each ply in parallel with the material and PAT streams representing the total stream. Average attributes for the entire sheet are passed in the PAT stream. Stream-average attributes which are useful are the orientation, formation, and wet strain undergone by the multi-ply sheet.

In the PROPS2 module, the paper properties are calculated. Handsheet properties are calculated for each ply based on the ply-specific performance attributes in the information stream and the handsheet forming conditions specified in the PROPS2 module. The machine paper properties such as STFI and Ring Crush are based on composite average elastic stiffness, $E_x$, $E_y$, and $E_z$ and the sheet total caliper and basis weight. The elastic properties for each ply are based on the pulp and network attributes for each ply stored in the information stream.

## CONSTRUCTION OF MAPPS MODEL FOR A LINERBOARD MACHINE

The linerboard paper machine produces linerboard in 45-90 lb/1000 sq. ft. basis weight range. Originally, the bottom layer furnish contained only virgin sw kraft furnish, but recently, recycled fiber has been added.

The width of the machine (wire) is 338 inches with a speed of 1830 ft/min, and the theoretical daily production is approximately 2400 t/d. Normal two-layer linerboard is produced with two headboxes and two fourdriniers.

A MAPPS flowsheet model for the machine was developed at the appropriate level of detail. The data needed to develop the model was taken from the following sources: P & I diagrams, mill personnel, and typical values based on information of other similar machines.

The process model, shown schematically in Fig. 26 through 29, is divided into four parts:

1. Top layer stock approach; blending, refining, screening, cleaning, and top wire forming.
2. Base layer stock approach; blending, refining, screening, cleaning, and top wire forming.
3. Wet pressing, drying, and calendering.
4. Fiber recovery and white water recycle.

The model structure is discussed below together with the information about the input data for the different modules. For detailed understanding of the individual modules, please refer to the MAPPS technical documentation (23, 38, 39, 40).

### Basic Design and Operating Conditions

As a starting point for the sensitivity comparisons and model validation, a base case was developed. All model parameters were adjusted to achieve reasonable agreement between base case properties and typical property information for linerboard of given grammage and furnish. At this stage no property information was provided from the mill. Design data and estimated operating conditions are presented in the following sections. Unless otherwise stated, these conditions are constant for all cases except where noted.

**Furnish and Fiber Inlet.** The model begins at the high density chests represented by stream initialization blocks, WOODO2. These blocks serve the dual purposes of initializing both the material/energy and the performance attribute streams for the furnish components. By means of module parameters, each WOOD02 block initializes the total mass flow, composition, temperature, pressure, and fiber characteristics of the entering fiber stream.

The same virgin fiber sw kraft pulp is used for top and bottom plies, and with the exception of fiber flow, identical WOOD02 blocks are used for both. Because the OCC is a mixture of hardwood (from medium in box waste) and softwood components, it is necessary to use two WOOD02 blocks to initialize the OCC.

The default values for all the fiber characteristics (Performance Attributes, PATs) for the incoming fiber are determined for each stream by specifying a default species. WOOD02 initializes all the PATs using the species database assuming the fibers have not been pulped or refined. To represent the pulping steps, or in case of recycled fiber, the former refining conditions, selected default PATs are overridden. The softwood components (recycled and virgin) originally refer to default values for southern pine (loblolly pine) and the hardwood component to gum. The effects of high-yield kraft pulping for sw and semichemical pulping for hw are represented by overriding the default pulp yield and kappa number with appropriate values. The effects of fiber recycle such as increased fiber stiffness and reduced freeness are accounted for by overriding the default freeness and fiber stiffness attributes with appropriate values.

The top layer, consisting entirely of virgin sw kraft, makes up 12% by weight of the whole sheet. The bottom layer consists of OCC and kraft in such proportions that OCC makes up 15% of the total fiber flow, and 20% of the OCC is hardwood.

Table 3. Initialization Parameters for the Fiber Flows.

| | SW Top | SW Bottom | OCC HW | OCC SW |
|---|---|---|---|---|
| % of total sheet | 12% | 73% | 3% | 12% |
| % of layer | 100% | 82.5% | 3.5% | 14% |
| Module | 1 | 29 | 27 | 28 |
| Total Flow rate *1000 lb/hr, | 604 | 2,816 | 127 | 483 |
| Moisture Content, fraction of total flow | .95 | .95 | .95 | .95 |
| Yield, %, | 55 | 55 | 74 | 55 |
| Kappa Number, | 95 | 95 | 46 | 95 |
| Freeness, CSF, | 740 | 740 | 300 | 450 |
| Fiber Length Distribution | | | | |
| Weighted average, mm, | 3.6 | 3.6 | 1.3 | 3.0 |
| Std. deviation, mm, | 4 | 4 | 3.5 | 7 |
| Fiber Width Distribution | | | | |
| Number Average, mm, | . 04 | .04 | .03 | .04 |
| Std. Deviation, mm, | 1.5 | 1.5 | 2.0 | 1.15 |
| Cell-Wall Thickness, microns | 3.5 | 3.5 | 6 | 3.5 |

The pulp within the fiber streams are broken down into a wide variety of components such as FINES, FIBER1, FIBER2 to FIBER9, and shive components, SHIVE1 through SHIVE3. Each of the fibers represent a specific range of fiber lengths based on Bauer-McNett screens. The shives represent pulp components which are retained on a Sommerville slotted screen with 0.1 mm width. The fiber length distribution is handled in two ways: by the actual flows of the fiber components and through the average fiber length and standard deviation in the PAT and multi-ply information streams.

**Refining.** Both the top and bottom layers are refined separately and in two stages. Every stage actually has three parallel refiners, but all parallel refiners are represented by one module. The recycled fiber is refined in one of the top layer secondary refiners. Consequently, two refiner modules are needed for virgin fiber in each layer. The recycled fiber passes through a series of base layer secondary refiners.

The HYRFNI module simulates the refining conditions. All the refiners are assumed to be atmospheric with minimal idle power loss. Specific power can be specified either directly or indirectly to the refiner. For an indirect specification, a power law model, based on plate gap, rotational speed, rpm, and inlet consistency is available. In the direct case used here, specific power is input directly for each refiner module.

The refiner "kinetic" parameters determine the change in fiber length and width distribution as a function of specific power load, consistency, and pulping yield. Each parameter is used to adjust one of the elements of the fiber length or width distribution leaving the refiner. For example, the first parameter controls the change in average fiber length, the second controls the change in the standard deviation of the fiber length distribution. The second set of parameters control the mean and standard deviations of the fiber width distributions. The model parameters were tuned to achieve the desired discharge CSF and fiber length distribution. A value of zero for a The parameters were then fixed and only the specific power was changed to predict sensitivity to refining. A second factor in the refining model involves the specific edge load theory of refining to determine the degree of fiber swelling. This submodel requires information on the plate geometry and rpm and was not used in this study. However, this feature will probably be required in future validation with the model.

The predicted freeness values from each of the refiners are shown at the bottom of Table 4. The top ply freeness drops to 510 ml at the discharge of the primary refiner and is reduced further to 395 ml at the discharge of the secondary refiner. The top ply freeness drops to 620 and 530 ml respectively at the discharge of the primary and secondary refiners.

Table 4. Refiner Conditions

| | Top | Top | Base | Base |
|---|---|---|---|---|
| Primary | Secondary | Primary | Secondary | |
| Module | 3 | 4 | 33 | 36 |
| Outlet pres. psi | 14.7 | 14.7 | 14.7 | 14.7 |
| Gross specific power hsp d/t | 4 | 0.8 | 2 | 0.7 |
| Idle pwr, fract. | 0.07 | 0.07 | 0.07 | 0.07 |
| Species | 3 | 3 | 3 | 3,17 |
| **Kinetic Parameters:** | | | | |
| mean length | 3.15 | 3.00 | 3.00 | 3.00 |
| stand dev. | -0.5 | -1 | -1 | -1 |
| mean width | 3.15 | 0.98 | 0.98 | 0.98 |
| stand dev. | 0 | 0 | 0 | 0 |
| Fiber swelling | 0.001 | 0.001 | 0.001 | 0.001 |
| Outlet Freeness (Predicted) | 510 | 395 | 620 | 530 |

**Blending and Consistency Control.** The top layer stock flow is diluted with white water from the top layer flat box seal pit and white water chest. Feed consistency to refiners is controlled to 3% by means of a CONSIS module.

Broke is mixed to the bottom layer virgin fiber flow mainly between the two refining stages (in refine chest) and after refining. As with the top layer, consistency is controlled with CONSIS modules. Refiner feed consistency is controlled at 3%. Before the last base refining stage, the OCC and virgin fiber flows are combined. White water from the base flat box seal pit and white water chest is used for dilution. All mixing is simulated with STOMIX modules. The STOMIX module determines the mixture attributes as well as the mixture composition and the thermodynamic properties of the stock mixture.

**Screening and Cleaning.** All screens, cleaners, and thickeners are modeled by means of the HYFRAC module by specifying a switch (1 = screen, 2 = cleaner, 3 = thickener) and the reject total flow split (reject ratio, % by volume) in the case of screens and cleaners or the discharge consistency in the case of thickener.

As a screen or cleaner, HYFRAC determines the separation of all components and the consistency of the overflow and underflow streams. In addition, HYFRAC determines the freeness and selected handsheet properties of the feed, accept, and reject streams. Rejects tend to be enriched in shives, while accepts tend to be enriched in shorter fibers. Reject ratios and feed consistencies used and the accept and reject consistencies and fiber losses calculated in the different screening and cleaning stages are presented in Table 5. Feed consistencies are controlled by means of CONSIS modules.

| Table 5. Screening and Cleaning Conditions | Mod No. | Feed Con | Acc. Cons. | Rej. Cons. | Reject Ratio | Loss |
|---|---|---|---|---|---|---|
| | | % | % | % | % | lb/hr |
| Top Layer | | | | | | |
| Top Primary Cleaners | 6 | .62 | .57 | 1.0 | 10 | |
| Top Screens | 7 | .57 | .53 | 1.9 | 3 | |
| Top Secondary Cleaners | 9 | .67 | .63 | 1.3 | 7 | |
| Top Tertiary Cleaners | 11 | .92 | .84 | 1.7 | 10 | |
| Top Final Cleaners | 13 | 1.7 | 1.5 | 4.9 | 4 | 31 |
| Bottom Layer | | | | | | |
| Base Screens | 41 | .70 | .65 | 2.5 | 3 | |

**Forming Section.** The whole paper machine, forming, wet pressing, drying, and calendering systems are modeled in three parallel sections to represent the possible CD variations across the machine. Presently, the conditions specified for the parallel modules are, however, the same, and CD variations are not predicted. These conditions are expected to vary in subsequent work using real-time data at the mill. Three FOUR01 modules represent the secondary headbox and top fourdrinier, while three FOUR01 modules represent the primary headbox and bottom fourdrinier in the initial section where the layers are formed separately. Three MPFORM modules represent the later section of the bottom fourdrinier where the top layer is couched on top of the bottom layer, and the two layers are drained together. The feed consistency of the multi-ply former is equal to the final consistencies of the sheet at the end of each of the Fourdriniers which are 7.3 and 7.4 % respectively.

The multi-ply draginage section does not involve gravity drainage or foila or wet vacuum boxes. Therefore, the data for these elements in Table 6 is set to zero. The multi-ply section involves only dry vacuum boxes. The wire resistance parameter in Table 6 is set to zero. This invokes the default resistance value which is 4.3 x $10^{6}$ 1/m.

Table 6. Forming Conditions

| | Top Fourdrinier | Bottom Fourdrinier | Multi-ply Former |
|---|---|---|---|
| Modules | 23,24,25 | 45,46,47 | 48,49,50 |
| Feed Consistency, % | 0.53 | 0.70 | 7.3/7.4 |
| Machine Speed, ft/s | 30.4 | 30.4 | 30.4 |
| Headbox: | | | |
| Jet/wire ratio | 0.990 | 1.09 | |
| Slice height, mm | 11.7 | 60 | |
| Pressure, psi | 14.7 | 14.7 | |

For both plies, the stock streams going to each CD section of the headbox are split into three equal parts. Each FOUR01 block represents the headbox, slice, gravity drainage forming board, foils, and vacuum boxes over one-third of the width of the machine. The MPFORM modules represent the two-layer drainage. In this section, all the drainage elements are suction boxes.

These modules compute the mass and energy flow and attributes of the mat, trim, and white water drained. The MPFORM modules also determine the undrained slurry. The slurry and mat streams of each CD position are recombined to represent the whole paper sheet.

Table 6. (Continued) Forming Conditions

| | Top | Bottom | Multi-ply |
|---|---|---|---|
| Forming | | | |
| Length, ft. | 3 | 6 | 0 |
| Foil section | | | |
| Length, ft. | 5 | 15 | 0 |
| Number | 2 | 3 | 0 |
| Angle, degrees | 5 | 5 | 0 |
| Foil length, ft. | 0.5 | 0.5 | 0 |
| Wet vacuum box section | | | |
| Length, ft. | 13 | 55 | 0 |

| Table 6. Continued. | Top | Bottom | Multi-ply former |
|---|---|---|---|
| Drainage and retention parameters: | | | |
| Wire resistance | 0 | 0 | 0 |
| Mat resistance | 520 | 80 | 80 |
| Foil coefficient | 1 | 1 | |
| 1st particle ret. par.. | .055 | .75 | .2 |
| 2nd particle ret.par. | 12 | 1 | 12 |
| White water cons.par. | -0.0012 | -0.0012 | -0.025 |

Stock is introduced into the primary headbox at 0.7% consistency and into the secondary headbox at 0.5%. The top layer is couched to the bottom layer at 7.3% consistency. The consistency at couch roll at the end of the MPFORM blocks is 25%.

Table 7. Forming Section Drainage Profiles.

| | Top | Bottom | MPFORM |
|---|---|---|---|
| | Fourdrinier | | |
| Cumulative drainage rate, cu ft/hr | | | |
| Forming board, | 68 | 187 | |
| Foils | 23809 | 127879 | |
| WVB's | 2772 | 130514 | |
| DVB's | 2906 | 161713 | 10656 |
| White water consistency, % | | | |
| Forming board | .119 | .178 | |
| Foils | .117 | .166 | |
| WVB's | .115 | .165 | |
| DVB's | .114 | .154 | .154 |
| Mat consistency, % | | | |
| Fiber inlet | .53 | .70 | 7.36 |
| Forming board | .53 | .70 | |
| Foils | 1.94 | 2.15 | |
| WVB's | 4.25 | 2.27 | |
| DVB's | 7.36 | 7.30 | 25.00 |

Among the calculations performed by the forming section modules are the initialization of the fiber contact area attributes, the sidedness, Z-D variability information, formation factor, fiber orientation and wet strain attribution, drainage profiles, basis weight profiles, white water consistency profiles, and sheet moisture profiles. Conditions are summarized in Table 6.

The calculated drainage profiles are shown in Table 7. Adjusting the forming modules so that all interrelated parameters were reasonable was difficult. Therefore, some values, such as white water consistency from MPFORM modules, differ from the target. The value is somewhat high but was accepted because the more important factors, such as retention and drainage rates were near the target.

**Press Section.** The press section consists of a lump breaker followed by two pressure nips. In the model, the lump breaker is assumed to be accounted for in the first press nip. Each CD location of each press nip is represented by a wet press model, WPRESS, which computes the degree of water removal and web consolidation as a function of lineal press load, felt number, felt basis weight, machine speed, press speed, and fiber characteristics such as freeness, yield, and cell-wall thickness. The attributes which are changed by the presses are the fiber contact areas, $S_{b1}$ and $S_{b2}$.

Press modules also determine the caliper of the sheet entering and leaving the nip based on the estimated degree of densification during pressing. The degree of sheet consolidation relative to water removal is determined by the compressive modulus, C. This variable was first adjusted to obtain reasonable dewatering levels for a given caliper change. After that, only the press loading was varied.

The web consistency increases from 25% entering the presses to 47.8% exiting the presses. The presses have a simple straight through configuration. Both nips are double felted.Under conditions of multi-ply forming, the MPFORM module generates a stream containing multi-ply attribute information. This information stream is passed to the presses to determine the consolidation within each layer. The press conditions are summarized in Table 8.

Table 8. Press Conditions.

| | First Nip | Second Nip |
|---|---|---|
| Modules | 58, 59, 60 | 61, 62, 63 |
| Machine speed, ft/min | 1830 | 1830 |
| Width, ft. | 9.23 | 9.23 |
| Number of felts | 2 | 2 |
| Top roll radius, ft. | 3.5 | 3.5 |
| Bottom roll radius, ft. | 3.5 | 3.5 |
| Felt basis weight, $g/m^2$ | 1313 | 1313 |
| Press speed, ft/min | 1820 | 1820 |
| Lineal nip pressure, lbf/in | 450 | 550 |
| Mat compressive modulus, GPa | 1.6 | 2.5 |

Table 8. Continued Press Conditions

| | First Nip | Second Nip |
|---|---|---|
| Optimum basis weight for dewatering $g/m^2$ | 337 | 337 |
| Moisture profile, % | | |
| Sheet dryness entering | 25 | 37.5 |
| Sheet dryness exiting | 37.5 | 47.8 |

Table 9. Dryer Conditions.

| | First Sect. | Second Sec. |
|---|---|---|
| Modules | 64, 65, 66 | 67, 68, 69 |
| Steam economy, steam condensed/ web water evaporated | 1.3 | 1.3 |
| Blowthrough ratio, steam blown through/ inlet steam | 0.15 | 0.15 |
| Steam pressure drop, psi | 40 | 40 |
| Web temperature rise, F | 10 | 10 |
| Leakage air ratio | -.02 | -.02 |
| Room temperature, F | 85 | 85 |
| Room humidity, fraction | .85 | .85 |
| Web stretch, stretch % | 0.6 | 0.6 |

**Dryer Section.** From the presses, the sheet is passed through two sets of dryer modules, DRYER, which represent two independently felted sections or dryer groups. Each DRYER module simulates a multi-can dryer system. The dryer consumes air and steam. The steam flow to the second dryer group is controlled by a PCONT2 module to achieve the desired final sheet dryness of 95%. The total cumulative MD stretch of 1.2% was specified over the two dryer sections. This stretch is one of the key factors contributing to the predicted MD/CD tensile and modulus ratios. The dryer input parameters and conditions are summarized in Table 9.

**Calendering** . The dry sheet from the dryers is then sent through a single-nip calender represented by a set of three CALEND modules, one for each CD location.

The CALEND model accounts for heat transfer in the nip and on the roll surface as well as the effects of wrap geometry, machine speed, roll temperature, roll radii, sheet basis weight, and speed differentials. The model also allows for moisture addition to the sheet by means of a steam or water stream. There are optional module parameters which can be used to adjust the sensitivity of the nip intensity factor, the factor described above. With the exception of compressibility, all module parameters were left at their default values.

Calendering is used to improve surface properties of the board such as roughness, porosity, gloss, etc. These properties are predicted in the model, but they have no relevance from the strength point of view and are not considered in this study. For the properties of interest, calendering changes sheet caliper, bulk, and internal bonding levels. The calendering effect is strongly dependent on nip loading and the response of the fibers to loading. Bonding or debonding behavior depends on the relationship between the sheet moisture and temperature and the thermal softening temperature of the fibers. However the moisture content must be above 10% in order for the calender to affect bonding levels. Because moisture was controlled to 6%-7%, bonding levels were not affected. The only effect of calendering in this case was an increase in the density and reduction in caliper. This had no effect on tensile or compressive strength.

For this reason calendering effects were not considered in the sensitively analysis. The module was tuned with the basic conditions and nip loading values so that the observed caliper under load and without load was in reasonable agreement. The compressibility parameter was used to adjust the nip intensity factor under a certain load level. The wrap parameter was set to 0 to indicate that the sheet passes directly through the nip without roll wrap. No change in MD sheet strain or orientation was assumed in the calender nip. All MD strain was assumed to be lumped into the dryer section. The basic calender input data is summarized in Table 10. Note that the units are all metric for the calender section.

Table 10. Calendering Conditions

| | |
|---|---|
| Modules | 73,74,75 |
| Calender Speed, m/min. | 620 |
| Nip Load, kN/m | 46 |
| Bottom Roll Temperature, C | 80 |
| Top Roll Temperature ,C | 80 |
| Bottom Roll, Radius, cm | 30 |
| Top Roll Radius, cm | 30 |
| Basis weight, $kg/m^2$ | 0.337 |
| Wrap | 0 |
| Stretch, % | 0 |

**Fiber Recovery and White Water Recycle.** The broke system and particularly the white water cycle have only a minor impact on paper properties under normal operating conditions. The broke and water system was, however, modeled with reasonable accuracy. Actual broke flows were not known. Outside broke, such as broke from PM 1, was not included in this study.

Basically, the trim and white waters from the top wire are kept separate and recirculated from the flat box seal pit back to the top wire. The wet broke, trim, and white waters drained from the base sheet and the total sheet are collected and passed through the save all for fiber recovery. These waters and water from the presses and vacuums are collected in white water chest for use in base sheet consistency control. The

Table 11. Fiber Recovery Conditions.

| | Top layer | Bottom layer |
|---|---|---|
| Broke % of total fiber flow | 0 | 21.4 |
| White water consistency | .02 | .05 |

broke and trim from the dried sheet and the fiber recovered in the save all are mixed into the bottom layer furnish between and after the base refiners.

The system is modeled using several STOMIX modules, SPLIT modules, and a SAVAL module to represent the save all.

**Moisture and caliper control.** The sensitivity comparisons were made at constant final dryness and sheet caliper by adjusting dryer steam flow rate and calender loading using PCONT2 blocks for each CD section. The module automatically changed the steam input in the last dryer section based on a P control algorithm using the deviations from target settings. The moisture control was more straightforward and worked better. Caliper is controlled by several factors and seemed to behave in a nonlinear fashion. In some situations, caliper control was inhibited due to a reduced sensitivity of final caliper to calender load.

## RESULTS AND DISCUSSION

### Sensitivity

The sensitivity of compressive strength to selected process conditions was determined with the model. The behavior of the model is discussed in the context of the experimental literature discussed previously. Future validation of the model will be based on a comparison with real-time mill data. A set 10 machine paper samples were tested at IPST after the sensitivity study was completed. These data are compared to the predictions for the base case in the sensitivity study in Table 12.

Because of the problems with the calender model, the predictions are of precalendered sheets. Based on the expected densification and reduction in caliper expected in the calender, the predictions are reasonable when compared to the mean property data and given the range in the data over the 10 samples. Sensitivity variables are 1. OCC content (% of the total furnish), 2. refining power, 3. press load, 4. fiber orientation, 5. formation, and 6. wet stretch. The comparisons were made at constant end moisture content and board caliper .

Figures 30 and 31 and Table 13 summarize the sensitivity of CD Ring Crush and Burst to a percentage change in each of the process variables. In descending order compressive strength was affected most by wet pressing, second by orientation and formation, and third by refining. The effect of drying restraint was lowest. Surprisingly, increased OCC content led to a small increase in compressive strength. This was believed to be primarily due to the too low OCC freeness assumed and the uncertainty associated with this variable. The effect of OCC content was not large, but it is expected that increased OCC will slightly decrease linerboard compressive strength. The predicted compressive strength, particularly Ring Crush, did not change with increased calender load. This trend was according to expectations.

The top ply fines retention and formation were poor compared to the base ply. That caused the top ply to be less bonded than the base ply. The base ply properties, however, dominated the composite properties. Top ply forming needs further attention in future usage of the model.

Table 12. Comparison of Base Case Predictions with Typical 2-ply Mill Properties

| | | IPST Lab Data | |
|---|---|---|---|
| | Base Case Predictions | Mean | Range |
| Basis Weight, $g/m^2$ | 342 | 330.7 | 324-344 |
| Caliper | 518 (precalendered) | 439 (calendered) | |
| Density, g/cc | 0.668 (precalendered) | 0.752 | 0.726-0.783 (calendered) |
| Burst (psi) | 153.5 | 158 | 150.8-169.6 |
| Burst Index | 3.2 | 3.3 | 3.02-3.52 |
| CD Ring Crush | 154.7 | 130.9 | 123-148.3 |
| CD STFI | 34.1 | 35.2 | 32.7-37.4 |
| Elastic Moduli (GPA) | | | |
| MD | * | 9.11 | 8.77-9.39 |
| CD | * | 3.9 | 3.66-4.12 |
| ZD | * | 0.04 | 0.035-0.047 |

Table 13. Sensitivity of the compressive strength

| Variable | Change % | Burst psi | CD Ring Crush lb /6 in |
|---|---|---|---|
| Base Case | | 153.5 | 154.7 |
| OCC content | 0-30 % | 149.6 to 155.6 | 148.6 to 158.8 |
| % Variation | -100 to +100 % | | |
| Refiner load Hsp d/t | 2 and 1 to 6 and 3 | 148.5 to 153.5 | 154.2 to 158.7 |
| % Variation | -50 to +50 % | | |
| Press load | 315,385-585,715 pli | 130.4 to 166.1 | 140.5 to 164.9 |
| % Variation | -30 to +30 % | | |
| Orientation | .35 to 2 | 153.5 to 190.1 | 156.3 to 129.7 |
| % Variation | -50,+100 % | | |

**OCC Content.** The typical OCC content is about 15% of the total sheet weight. OCC was set to two levels, 0 and 30% by weight. OCC is used only in the bottom layer. The key factor in predicting the effects of OCC content are the values of the OCC fiber PAT's in the high density chests. These characteristics were not accurately known at this stage of the validation. This factor may have caused some errors in these results which can be corrected in later work with more accurate information.

The sensitivity of selected end-use properties is shown in Table 14. The sensitivity of CD STFI and CD Ring Crush is shown in Fig. 32.

Table 14. Effects of Different Levels of OCC

Properties of the final sheet

| | 0 % | Base | 30 % |
|---|---|---|---|
| Basis weight, g/m2, (as is | 337 | 342 | 342 |
| MD tensile strength, | 5.15 | 5.25 | 5.34 |
| CD tensile strength, | 4.60 | 4.69 | 4.77 |
| MD/CD tensile ratio | 1.12 | 1.12 | 1.12 |
| Burst, psi | 149.6 | 153.5 | 155.6 |
| Sheet density, g/cc | 0.644 | 0.665 | 0.680 |
| Stretch, % | 1.93 | 1.98 | 2.01 |
| Caliper, mils | 20.82 | 20.4 | 20.03 |
| CD STFI, lb/in | 33.1 | 34.1 | 34:7 |

The model predicts a small sensitivity to OCC content. The OCC effect is the smallest of the seven process variables. The compressive strength seems to improve with increased OCC content and to decrease with no OCC in the furnish. This result seemed surprising and was investigated further. The improvement in the compressive strength with increasing OCC was a result of the lower freeness assumed for the OCC. If OCC freeness was changed to the level of the virgin fiber, the increased OCC did not affect the compressive strength.

The fiber property which contributes significantly to bonding potential is fiber bending stiffness. Among other factors, this property is affected by drying the fibers. When fibers are dried, they become stiffer. Some fiber fractions do not rewet and return to their predried condition. This effect, sometimes referred to as hornification, is important in repulping and secondary fiber use. In MAPPS, this is accounted for by a fiber stiffness factor, SMOD, which increases when the fibers are dried above a critical level (93%). Although SMOD for OCC was set higher than for virgin fiber, this seemed to have little effect on bonding level. The fiber length was somewhat lower for the input OCC fibers compared to that of virgin fiber. However, this effect was also masked by other variables, particularly CSF.

The fiber modulus in the input should have been lower for the OCC. That would have decreased the compressive strength of the ply containing the OCC relative to the ply containing virgin fibers resulting in a somewhat lower compressive strength for the composite.

Increased calender loads did not change the actual bonded area, ASB, used to determine bond density. This indicates that the calender conditions were not debonding. However, when comparing cases at constant caliper but different OCC contents, a lower calender load was required to compress the 30% OCC sheet to the required caliper compared to be the 15% base case.

**Refining.** The effect of changes in refining power was studied. The power was changed from 4 Hpd/t and .8 Hpd/t in top primary and secondary refiners, respectively, to 2 and 6 Hpd/t and .5 and 1 Hpd/t in the cases tested. The base refiner power was reduced from 2 and .7 Hpd/t to 1 and 3 and increased to 4 and 9 respectively, in the primary and secondary refines. The sensitivity to refining is shown in Table 15 and Fig. 33.

As expected, the sheet compressive properties improved with increased refining and decreased with less refining. Refining increases strength and modulus both by increasing densification and by increasing fiber tensile and fiber modulus. However the positive effects of increased fiber tensile and bonding are offset by decreased fiber length. The effect seen from refining was, however, somewhat less sensitive than expected. The effect was weakened by the fact that the OCC portion of the furnish was already slightly refined. Broke and fines recyle led to significant differences in CSF throughout the process. The headbox freeness is lower than the CSF in the broke chest for example. However, at the fines retention levels in the process, the resulting sheet fines did not change as much with refining as did the headbox CSF. Thus, the primary component of the refining, namely fines, resulted in higher white water fines and lower CSF with only a small effect on the final sheet.

The important effects of refining, fiber separation and surface area development, are accounted for through the use of the fiber length distribution parameters, AVGL and SIGL and Canadian Standard Freeness, CSF. Other effects of refining, such as swelling, increased flexibility, and bonding potential are accounted for with attribute SMOD.

Table 15. Effects of Refining Power on Compressive Strength Properties of the Final Sheet

| | Low | Base | High |
|---|---|---|---|
| Basis weight, g/m2, (as is) | 342 | 342 | 342 |
| MD tensile strength | 4.83 | 5.25 | 5.41 |
| CD tensile strength | 4.31 | 4.69 | 4.83 |
| MD/CDtensile ratio | 1.12 | 1.12 | 1.12 |
| Burst, psi | 148.5 | 153.5 | 158.4 |
| Sheet density, g/cc | 0.648 | 0.668 | 0.688 |
| Stretch, % | 1.94 | 1.98 | 2.02 |
| Caliper, mils | 21.2 | 20.4 | 19.75 |
| CD STFI,lb/in | 34.0 | 34.04 | 34.7 |
| CD Ring Crush, lb/6 in width | 154.2 | 154.7 | 158.7 |

The refining level is best compared through CSF. Freeness was initialized in the WOOD02 modules. Lower values were used for recycled fiber than for virgin fiber components. The lower values for recycled fiber and the recycle of broke, particularly the recovered and recycled fines and lower freeness of white water, lowered the base layer freeness at the headbox. The headbox freeness is not extremely important since the fines which are recycled are not retained in the sheet. The headbox freeness controls, however, the drainage rates and moisture profiles. Its effect on dry sheet properties may be sometimes overstated. The effect of changing refining power was obscured because the headbox freeness was affected by other factors and was not directly related back to refining power. Even though the headbox CSF was not changed, the dry sheet CSF did shift downward with increased refining. However, this factor is only a part of the refining effect. The second part, namely, fiber swelling, was not changed in the current study due to the lack of information on the plate geometry and RPM required to use the swelling model. This fact could account for the reduced sensitivity to refining.

**Press Load.** The base case press configuration was 450 pli and 550 pli in the first and second nip, respectively. Press loads were varied around this value by 30% for both nips (i.e., 315 and 585 pli and 385 pli and 715 pli, respectively). The exiting sheet dryness after the press varied from the base value of 47.8% to a low of 39% and a high of 58.9%. The high case dryness is unattainable and unrealistic. The press module is, however, very sensitive to the press load, and the loads used in the high load case are not exceptionally high. On the contrary, extended nips have loads an order of magnitude higher than values used here. The results are summarized in Table 15. and Fig. 34.

Compressive properties were most sensitive to wet press load. This strong effect is in general agreement with the sensitivity found in the literature. However, the simulation may be somewhat too sensitive to the press loading. This factor should be evaluated more thoroughly in future work.

An increase in press load of 30% increases the potential bonded area by 38%. When the potential bonded area is increased, there is a corresponding increase in actual bonded area, ASB, after drying and, consequently, bond density and effective bond density. This increase leads directly to an increase in compressive strength provided the sheet caliper is kept constant. If the sheet instead is calendered with constant load, the same load as in the base case, the sensitivity to increased pressing is lower. This shows that sheet caliper has a partial effect on compressive strength as can be seen from the predicting equations where elastic stiffness, Et, is used. If the sheet caliper is reduced in the press and not compensated with reduced calendering, the compressive strength increases less.

Table 16. Effect of Press Load on Compressive Strength

Properties of the final sheet

| | 70 % | Base | 130 % |
|---|---|---|---|
| Basis weight, g/m2, (as is) | 342 | 342 | 342 |
| MD tensile strength | 4.34 | 5.25 | 5.53 |
| CD tensile strength | 4.17 | 4.69 | 4.94 |
| MD/CDtensile ratio | 1.12 | 1.12 | 1.12 |
| Burst, psi | 130.4 | 153.5 | 166.1 |
| Sheet density, g/cc | 0.576 | 0.668 | 0.718 |
| Stretch, % | 1.79 | 1.98 | 2.08 |
| Caliper, mils | 23.81 | 20.40 | 18.92 |
| CD STFI,lb/in | 31.92 | 34.09 | 35.65 |
| CD Ring Crush, lb/6 in width | 140.5 | 154.7 | 164.9 |

**Formation, Fiber Orientation and Stretch Coefficients.** Variations in sheet properties, i.e., sheet anisotropy, is accounted for by means of three factors: formation, fiber orientation coefficient, OR, and wet stretch factor, WS. OR and WS are not predicted in MAPPS due to the wide variety of factors which can affect these variables and the lack of data relating orientation to headbox and other forming conditions. The wet stretch should be readily obtainable based on the speed differentials along the

Table 17. Effect of Formation on Compressive Strength

Properties of the final sheet

| | Sheet Properties | |
|---|---|---|
| Formation Coefficient | 0.5 | Base |
| Basis weight, g/m2, (as is) | 342 | 342 |
| MD tensile strength | 2.56 | 5.25 |
| CD tensile strength | 2.29 | 4.69 |
| MD/CDtensile ratio | 1.12 | 1.12 |
| Burst, psi | 57.71 | 153.54 |
| Sheet density, g/cc | 0.668 | 0.668 |
| Stretch, % | 1.17 | 1.98 |
| Caliper, mils | 20.40 | 20.40 |

machine. Although not predicted, there are several operations in which these variables can be introduced by the used. These attributes are then passed along and ultimately affect properties of the sheet. In the case of stretch, MD restraint is additive and can therefore, accumulate along the machine from the end of the forming wire to the end of the dryer or calender section. Orientation is essentially built in the forming section due primarily to differences in jet to wire velocity.

The stretch in drying, expressed as a percentage, can also be negative representing shrinkage. The net stretch is additive and therefore generally increases along the machine. Basis weight uniformity, formation, is represented by the formation coefficient which varies from 0 to 1, where 1 represents perfect formation. The formation coefficient is initialized in the forming module FOUR01. The formation model is sensitive to headbox consistency, fiber length, jet-to-wire speed ratio, and freeness. However, as basis weight increases, the effects of these variables diminishes, and the formation index tends to increase. This is not to say that formation is improved with increasing basis weight. Rather, the influence of formation on bonding (effective bond density), tensile and compressive strength tends to decrease.

Thus, for high basis weights seen in liner and corrugating medium, formation is no longer sensitive to changes in headbox stock consistency. The coefficient was 1 for the bottom layer but only about 0.5 for the top layer. The base layer formation value dominated. The value in the property calculation was 1. In the current version of MAPPS, these coefficients are all passed on in the PAS-streams as averages of the two plies and not separately for each ply. However, in new developmental versions, all PAT values are passed in the information stream for each ply resulting in more complete information for the multi-ply calculations. The results of the coefficients are given in Tables 17, 18, and 19 and in Figs. 36, 37, and 38.

The expression used to predict the MD to CD tensile ratio is a function of the orientation ratio, OR, defined previously, and the net MD stretch. In the future, this relationship will be improved to include the CD stretch. The relationship, based on data from Setterholm (64 ,65), is given by

$$RMDCD = 0.335 - 0.585\ WS + 0.708\ WS\ OR + 0.6345\ OR^2 \qquad (22)$$

WS refers to the MD wet stretch in percent. As the fibers becomes oriented more in the cross direction, OR decreases to zero. orientation angle increases toward 90 degrees and OT decreases toward zero. As OR decreases to zero, the MD/CD tensile ratio (RMDCD) becomes incdependent of OR. In the limit, we obtain,

$$RMDCD = 0.335 - 0.585\ WS \qquad (23)$$

As the wet stretch decreases, the ratio approaches 0.335. Thus at high CD orientations and no net stretch, the ratio approaches 0.335 (CD tensile is about 3 times MD tensile). Of course, this condition is never actually observed commercially and probably not experimentally. As MD stretch increases above zero, RMDCD becomes negative and the model is no longer valid. Actually, the results for combinations of WS and OR for which RMDCD is less than 0.5 are probably not realistic.

The ratio of MD to CD elastic modulus is determine by the actual values for each elastic constant model. The models for the elastic constants were obtained from completely different work by Fleischmann. However, it is interesting to note that the ratio of elastic constants is very close to that predicted by the above model for the tensile strengths for the same stretch and orientation and sheet density.

The base level of wet stretch was set at 1.2 % and orientation (OR) at 1.0 (a random sheet). Normally, the base conditions are set to typical values. However, the choice of OR of 1.0 is not typical of the conditions which would be produced on a high speed liner machine. Under these conditions, the predicted MD/CD tensile ratio is only 1.12. However, the high level orientation (OR) = 2 is certainly at the high end of the range. For a stretch of 3% and OR = 1, RMDCD = 1.34. The quadratic term in OR makes the dependenc stronger for fiber orientation than for stretch. For OR = 2 and WS = 1.2, the ratio increases to 3.87 while for low OR of 0.35 and WS = 1.2, the ratio drops to an unreasonable level of 0.008. For this condition the ratio is set at 1.0

The sensitivity to the coefficients was very reasonable. As predicted in the literature, the increased fiber orientation tended to increase MD compressive strength at the expense of CD strength, while increased wet stretch tended to improve both MD and CD strength. A decreased formation led to lower compressive strength. The effect was very sensitive, particularly in CD direction.

**Fiber Orientation and Wet Stretch**

The effects of fiber orientation and wet stretch are significant because they determine, to a large extent, the differences between the MD, CD and ZD moduli which in turn influence the compressive properties. Also machine direction restraint (MD Stretch) tends to reduce the value of elongation at break in the tensile test. This results in a reduction in burst. Also a net MD stretch increases MD tensile at the expense of CD tensile. However, the geometric mean tensile is not affected. Fig. 36 shows that burst increases with increasing MD orientation. As orientation coeffiecnt increases from 1.4 to 2 (i.e., increased MD orientation, cotangent of the angle with the MD direction), burst increases significantly from 153 to 190 psi. CD Ring crush behaves in just the opposite way, remaining relatively insensitive to orientation from 1 to 1.5 and decreasing with increased orientation factor. This results from a significant shift in the values of the MD and CD moduli and strength from 1.12 at 1 to 2.34 at 1.5 and to 3.87 at 2.0.

The effects of wet stretch are analogous but reversed. For low levels of wet stretch (0.2 to 1 %), burst decreases with increasing wet stretch while CD ring crush increases. Above 1.4 to 1.5 % both burst and ring crush are somewhat sensitive to stretch but the trend continues. The decrease in burst with MD stretch is due to the decrease in elongation at break which results in a lower burst. The increase in CD ring crush is due to an increase ZD modulus. The reduction of CD modulus is compensated somewhat by an increase in MD modulus.

Table 18. Effect of Fiber Orientation on Sheet Properties

| Orientation Coefficient | .35 | Base(1) | 2 |
|---|---|---|---|
| Basis Weight g/sq. m | 342 | 342 | 342 |
| MD tensile strength | 5.25 | 5.25 | 14.1 |
| CD tensile strength | 4.69 | 4.69 | 3.64 |
| MD/CDtensile ratio | 1.12* | 1.12 | 3.87 |
| Burst, psi | 153.5 | 153.5 | 190.1 |
| Sheet density, g/cc | 0.668 | 0.668 | 0.668 |
| Stretch, % | 1.98 | 1.98 | 1.98 |
| Caliper, mils | 20.4 | 20.4 | 20.4 |
| CD STFI,lb/in | 35.2 | 34.09 | 21.23 |
| CD Ring Crush, lb/6 in width | 156.3 | 154.7 | 129.7 |

Table 19. Effect of Wet Stretch on Compressive Strength

| | Properties of the Final Sheet | | |
|---|---|---|---|
| | 0.2 % | Base 1.2 % | 3 % |
| Basis weight, g/m2, (as is) | 342 | 342 | 342 |
| MD tensile strength | 4.96 | 5.25 | 5.72 |
| CD tensile strength | 4.96 | 4.69 | 4.30 |
| MD/CD tensile ratio | 1.00 | 1.12 | 1.33 |
| Burst, psi | 171.8 | 153.5 | 137 |
| Sheet density, g/cc | 0.668 | 0.668 | 0.668 |
| Stretch, % | 2.48 | 1.98 | 1.58 |
| Caliper, mils | 20.4 | 20.4 | 20.4 |
| CD STFI,lb/in | 33.9 | 34.09 | 34.09 |
| CD Ring Crush, lb/6 in width | 146.0 | 154.7 | 161 |

## CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The model predicted the sensitivity of linerboard compressive strength to several important process variables reasonably well considering the uncertainty in some of the input data. Some problems or discrepancies were found in the calender model. These were related to constraining the maximum level of densification consistent with the independent sheet density model. These corrections have been implemented and are being tested at the present time. The sensitivities to press loading were probably too great, while the sensitivity to refiner loading was too low. These effects should be carefully examined in future validation work. Attention should be given to the effect of pulp freeness relative to other fiber properties. Recycled fiber should influence sheet properties through freeness and other factors such as fiber stiffness.

The project also fulfilled another important purpose namely in checking and correcting the multi-ply property system for consistency with general engineering data. The model worked well, but several corrections and improvements were required to achieve the final results. Some correction to the model will undoubtedly be required in future work. One area which should be looked at is the detected basis weight loss from the top ply in the multi-ply former. Base case property data generally agreed with typical mill data measured off-line at IPST.

The PAT models can now be applied to the actual validation study using real-time mill process and product data. The program has been found to work and is ready for on-line validation..
In the future, the model will be most useful for optimization of compressive strength properties such as Ring Crush and STFI.

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# APPENDIX A

Figure 1. Edgewise Compressive Strength vs. Density (Loblolly Pine) (4).

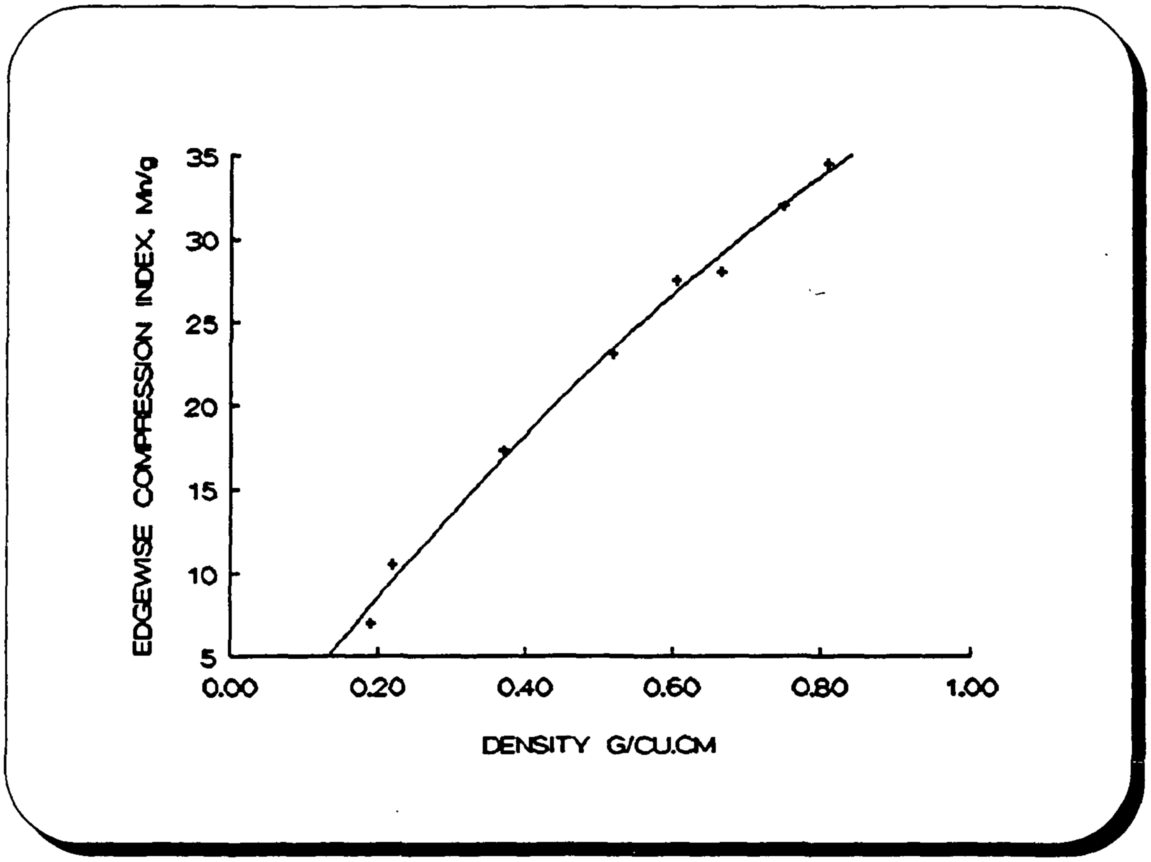

Figure 2. Coordinates for the Pincipal Directions of Paper (41).

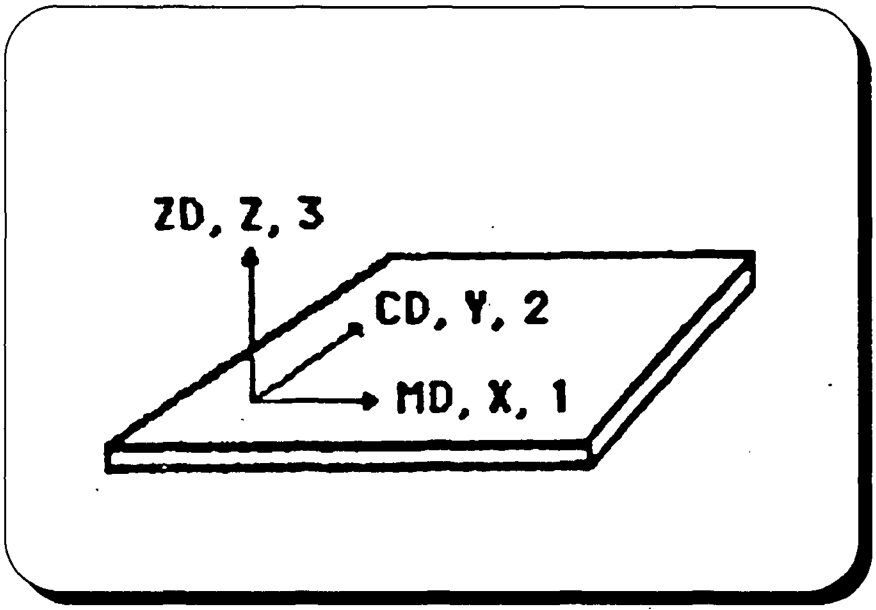

Figure 3. The Effect of Fiber Properties and Papermaking Conditions on Elastic Modulus of Paper (13).

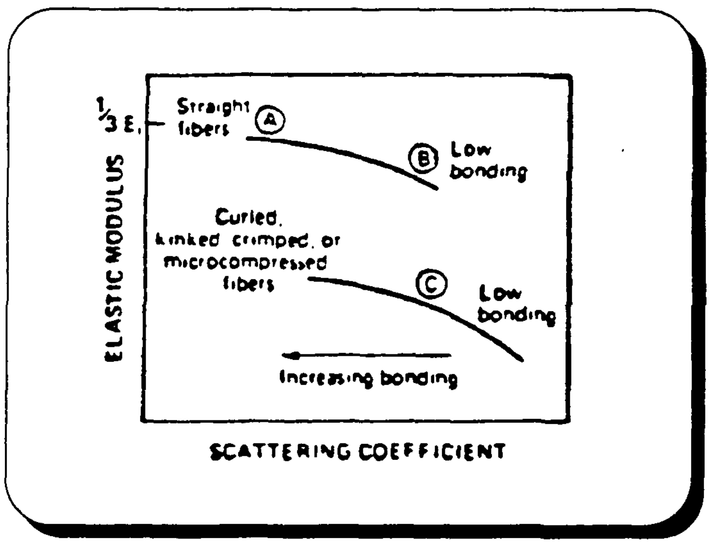

Figure 4. Relationship of STFI to Elastic Stiffnesses (10).

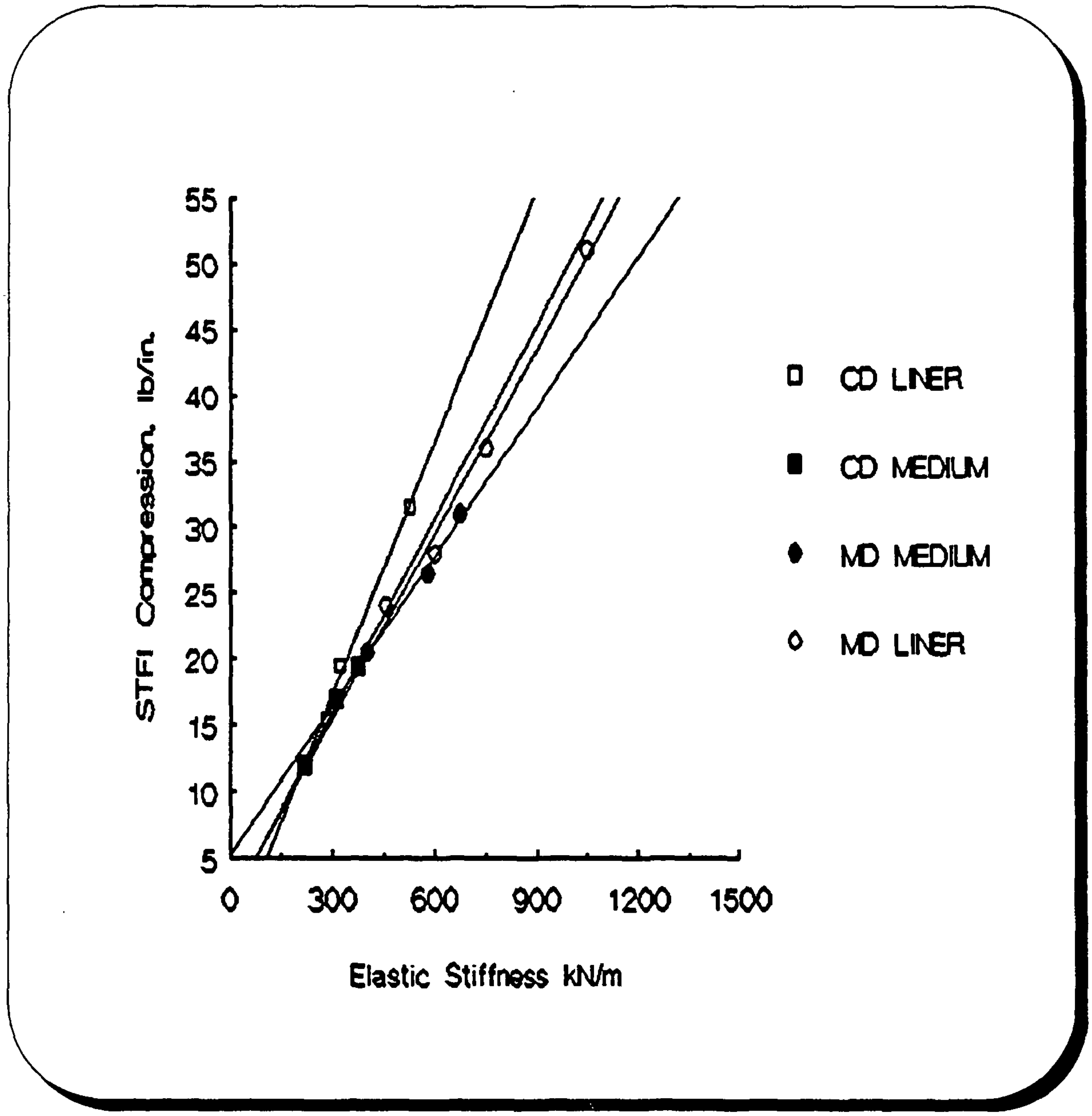

Figure 5. Relationships Between Ring Crush and Elastic Stiffnesses (10).

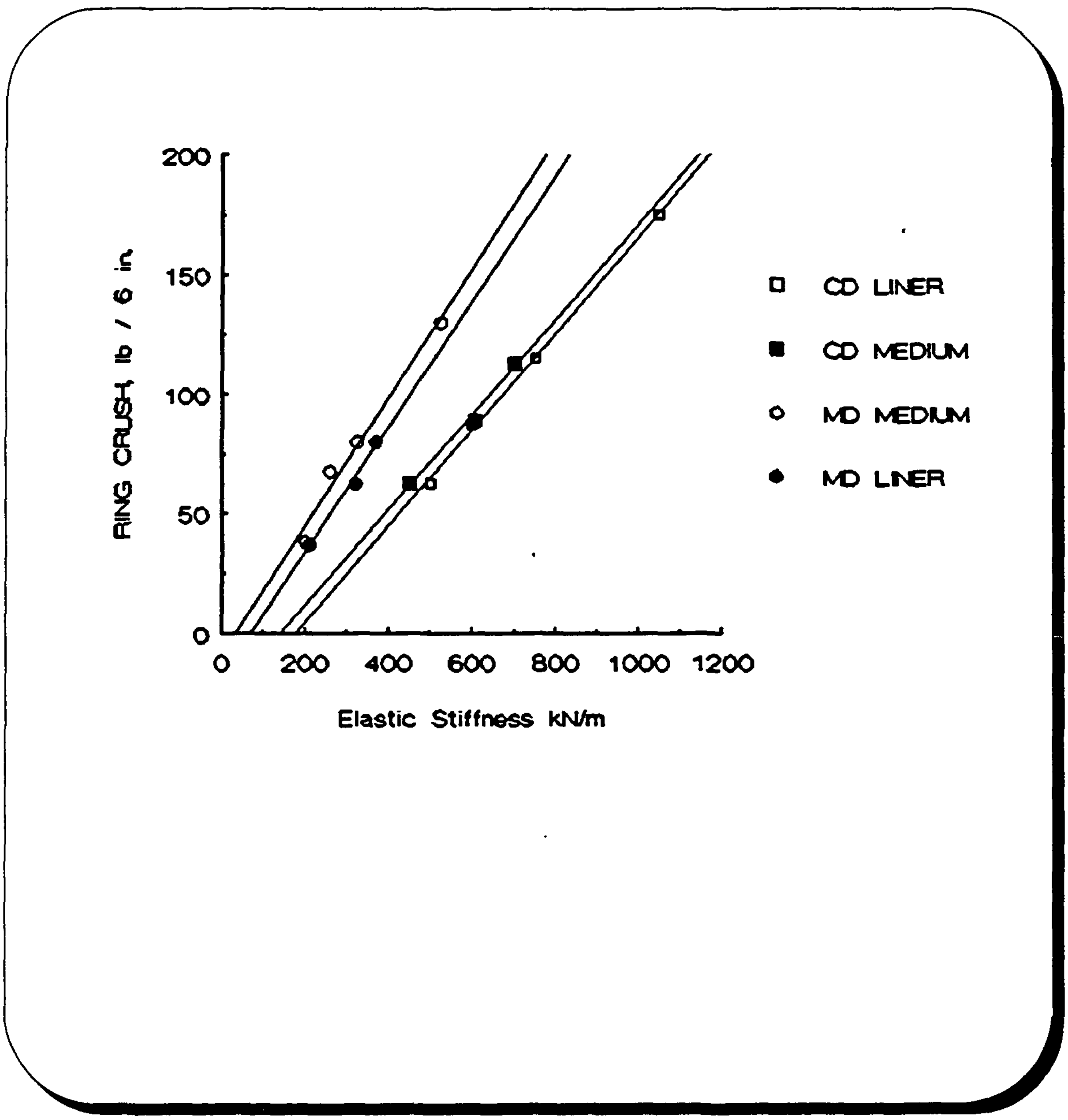

Figure 6. Relationship between Compressive Strength and Fiber Modulus.

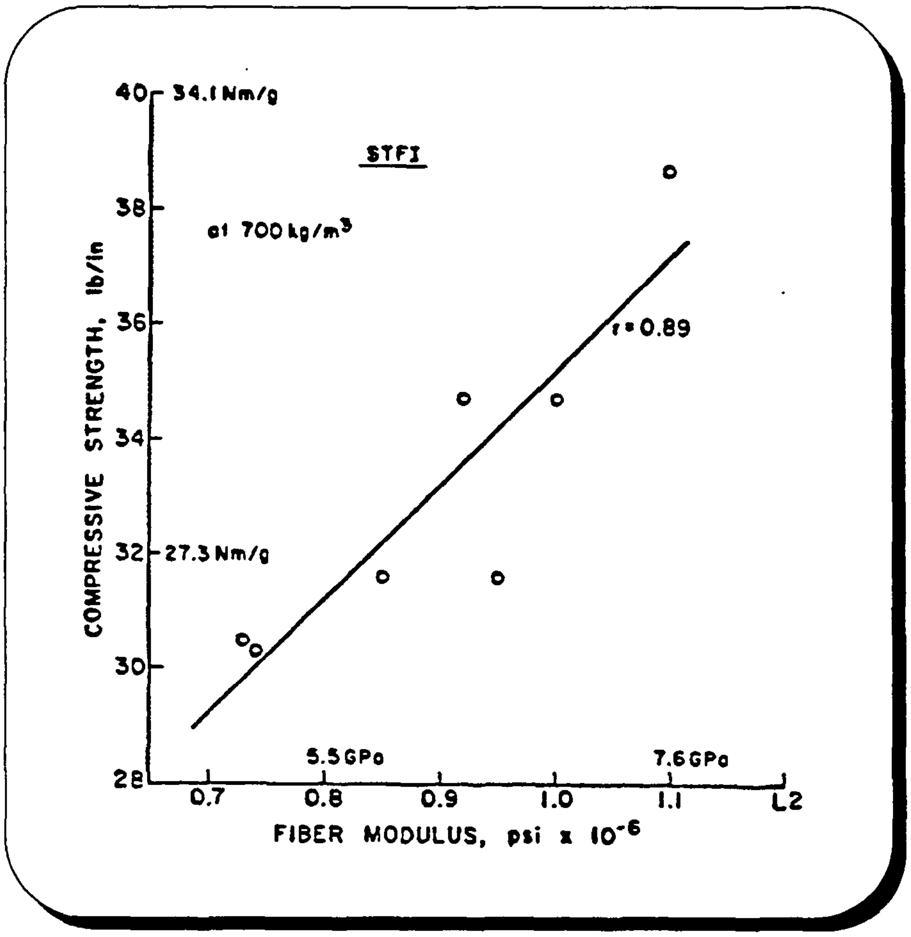

Figure 7. The Effect of Linerboard Thickness and Modulus of Elasticity on Container Compressive Strength (1).

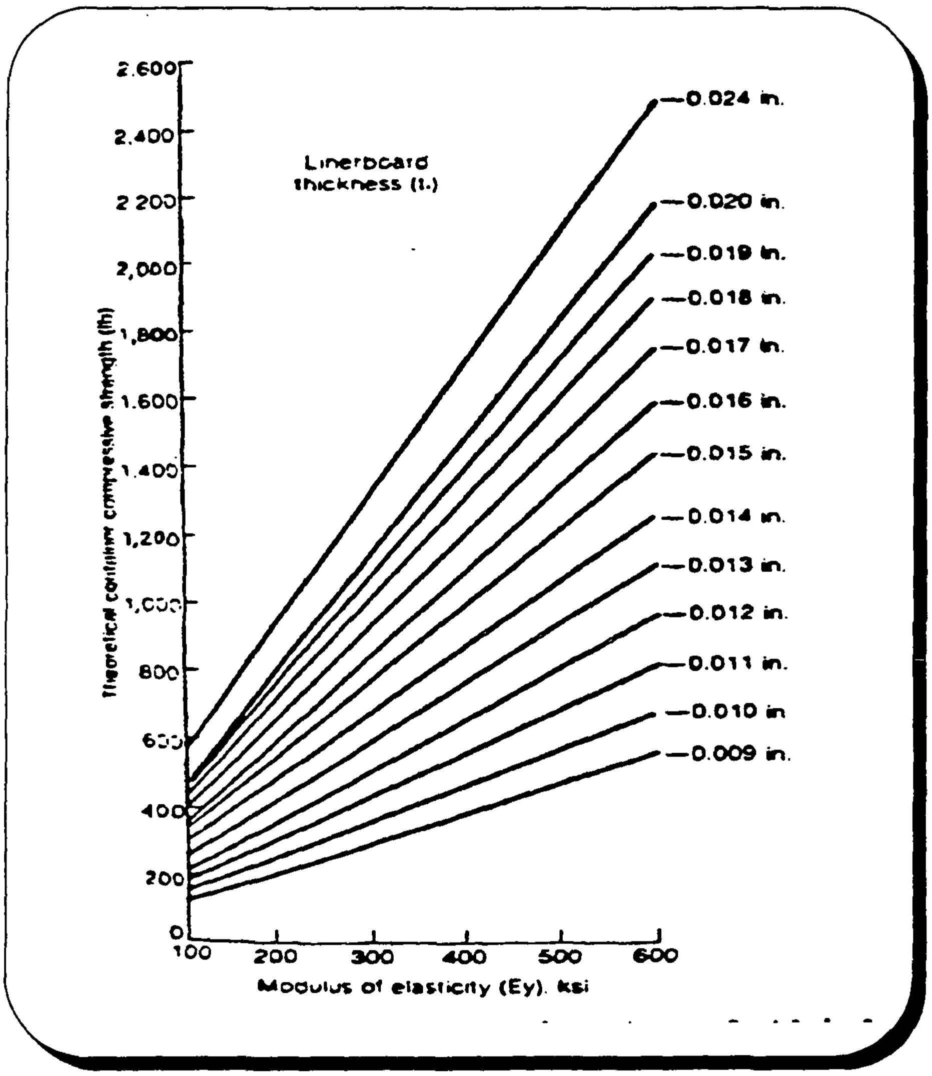

Figure. 8. The Effect of Formation on Compressive Strength (6).

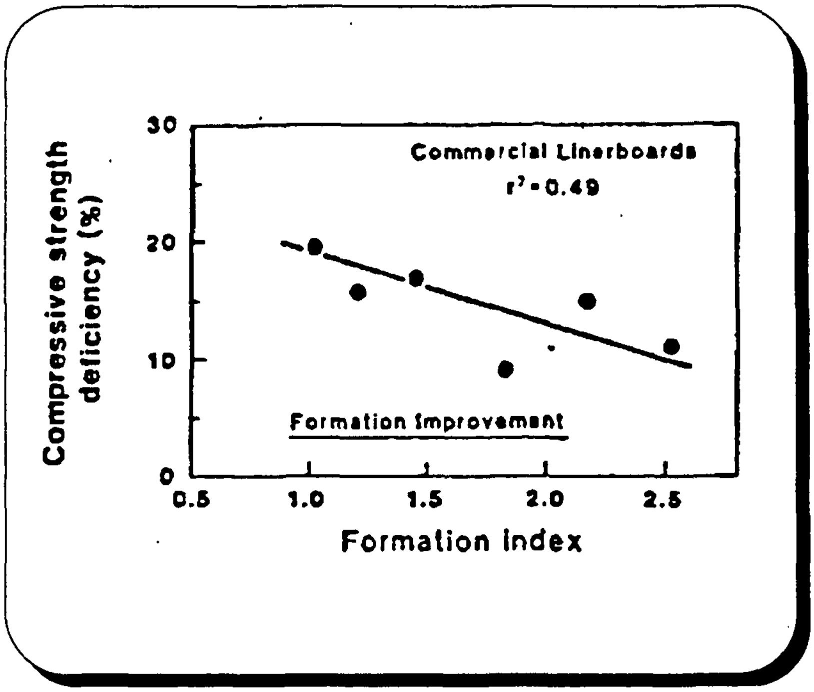

Figure 9. Compressive Strength vs. Tensile Ratio (14).

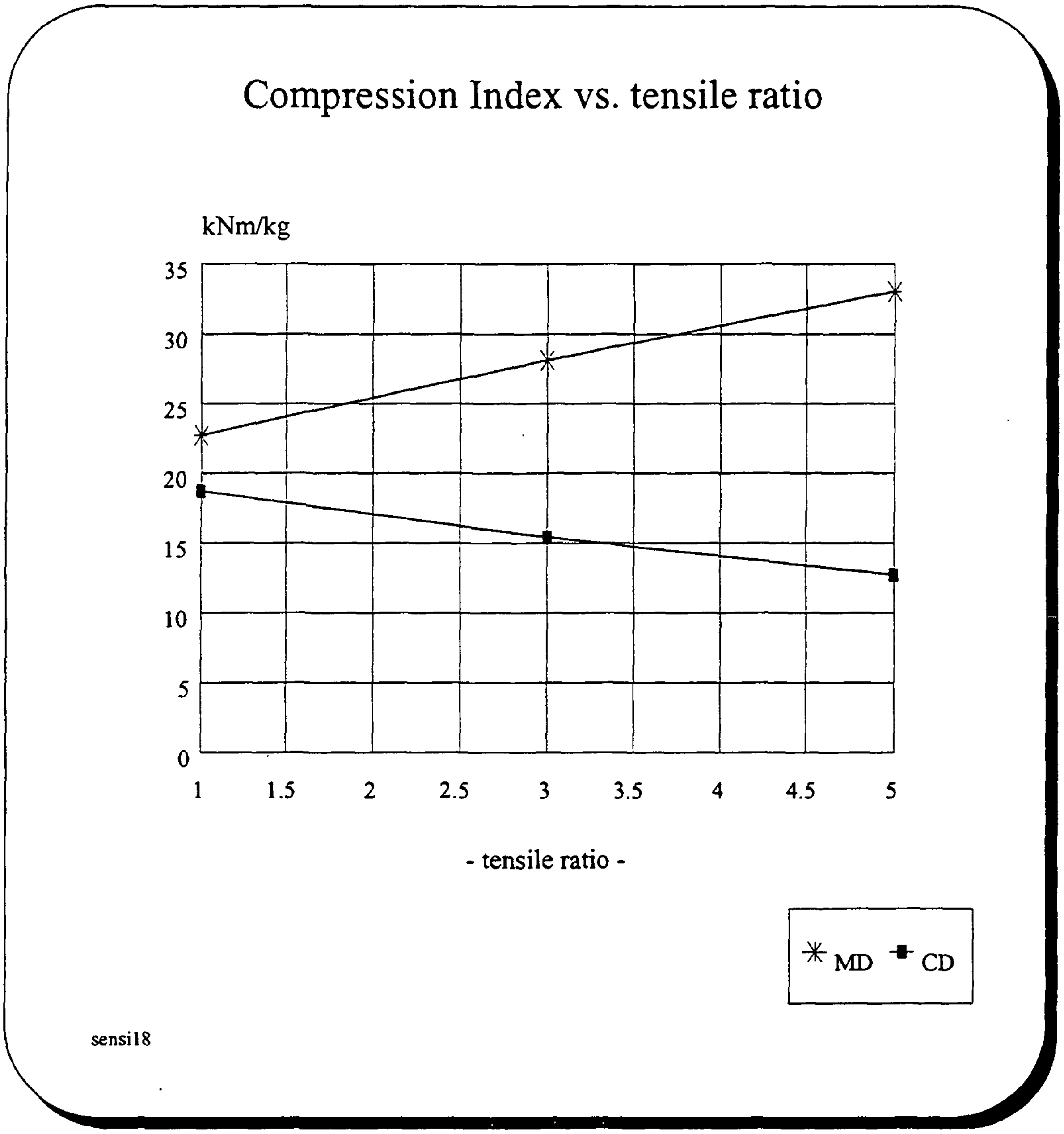

Figure. 10. Compressive Strength vs. Wet Pressing Pressure for Sheets from Pulps of Various Species, SW 650 CSF, HW 500 CSF (5).

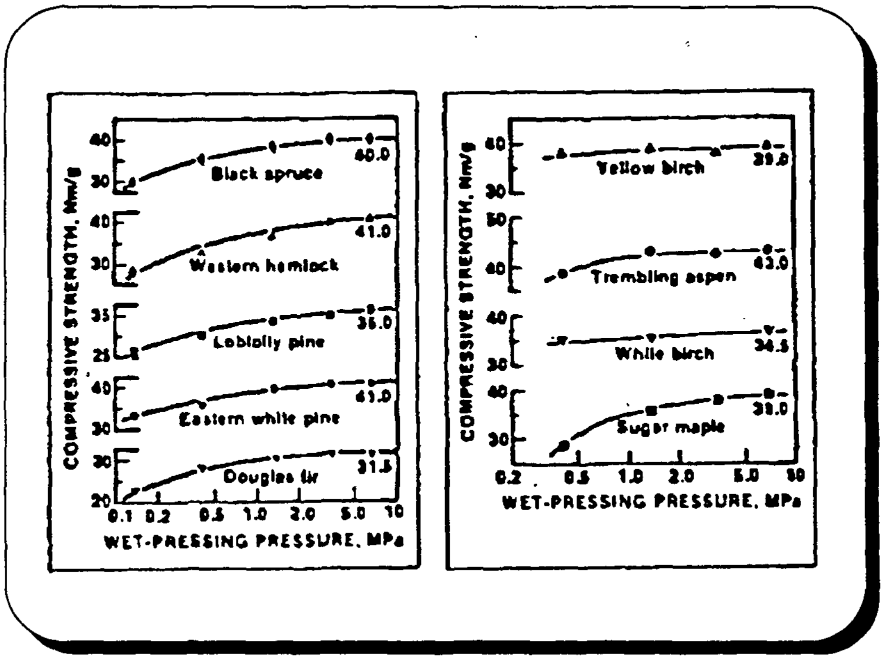

Figure 11. Fiber Elastic Modulus Variation with Fibril Angle for Spruce, 45 % Yield Kraft Fibers (26).

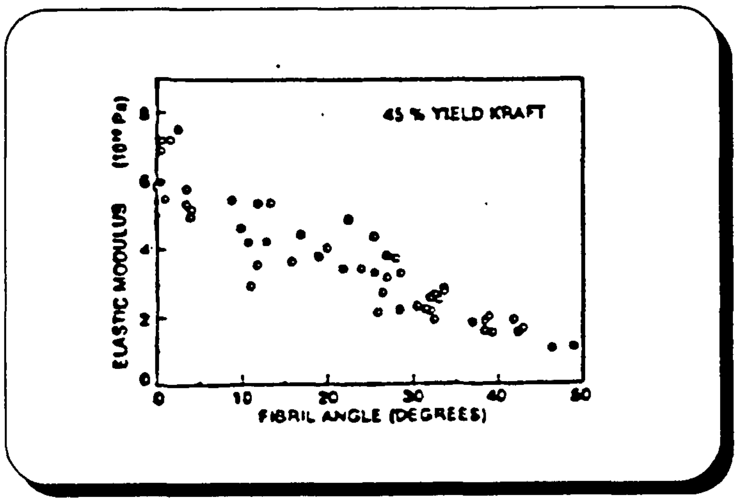

Figure 12 . Compressive Strengths of Various Fiber Types (4, 31).

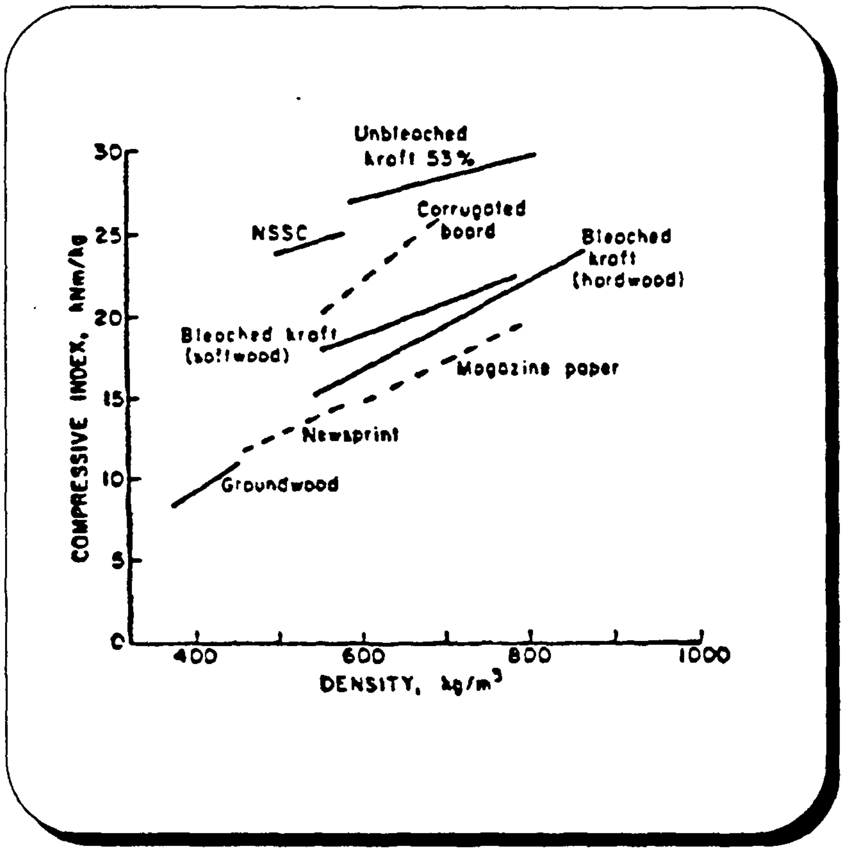

Figure 13. The Effect of Beating and Wet Pressing on Compressive Strength for Paperboard Made from Kraft Pulps of Different Yields (14).

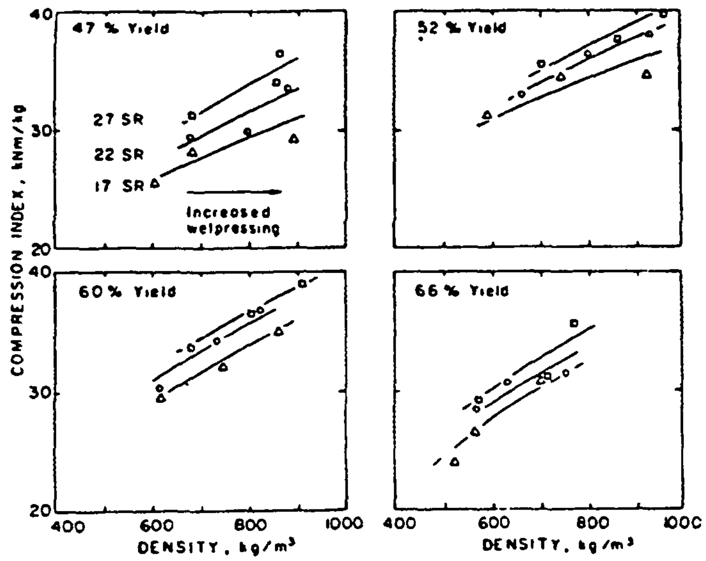

Figure 14a. Strength in Tension and Compression.

Figure 14b. Strain to Failure for Paperboard Made from Pulps of Different Yields at Constant Density, 650 kg/ cu. m.

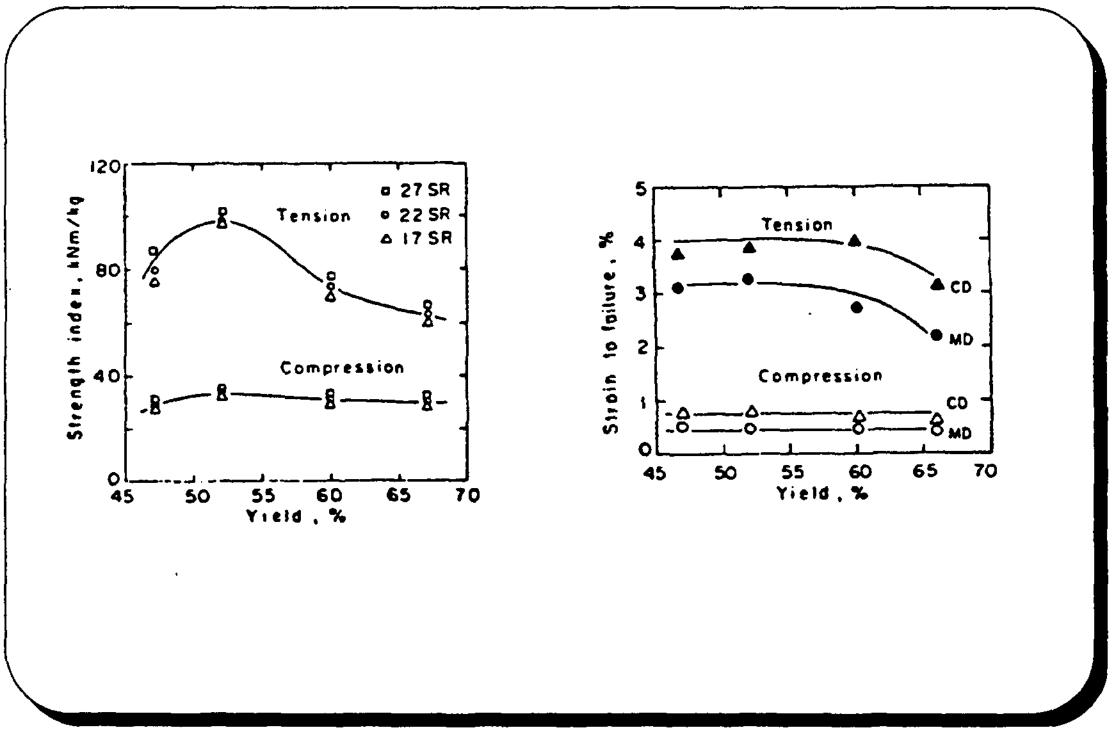

Figure 15. The Effect of Introducing Shives of Different Sizes on the Strength Properties of Paperboard (6).

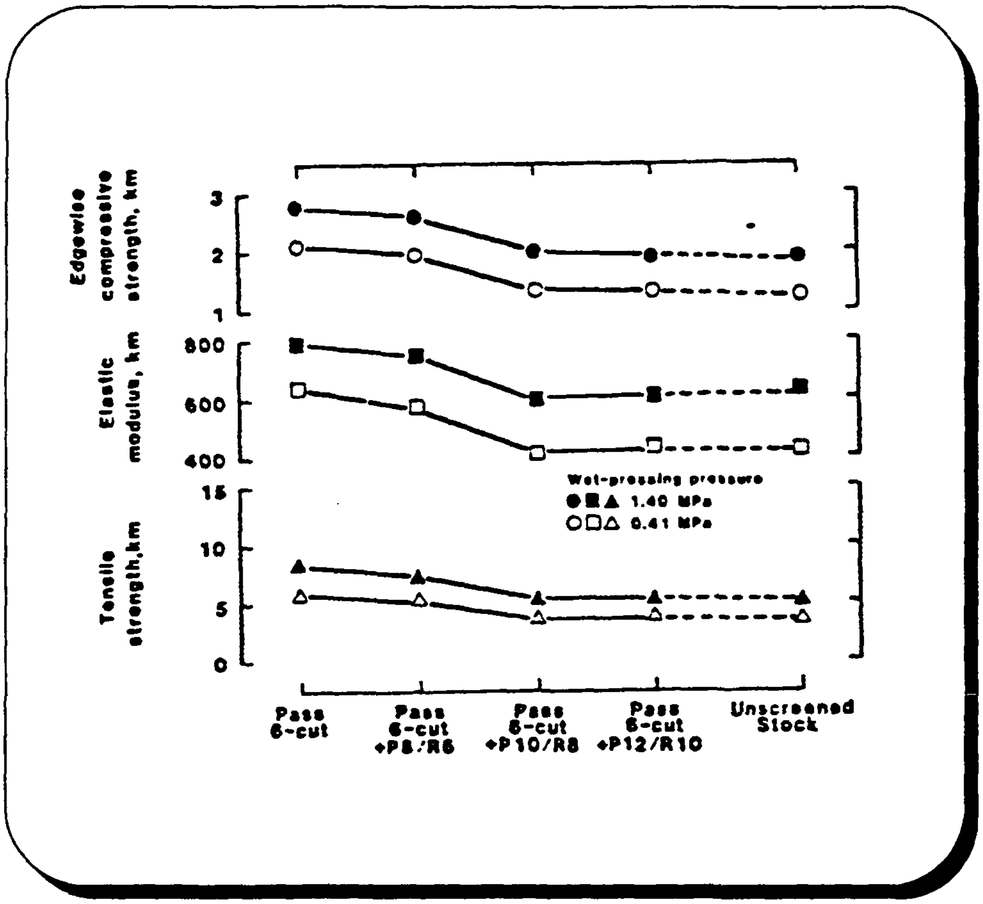

Figure 16. The Effect of Refining Variables on Ring Crush (1).

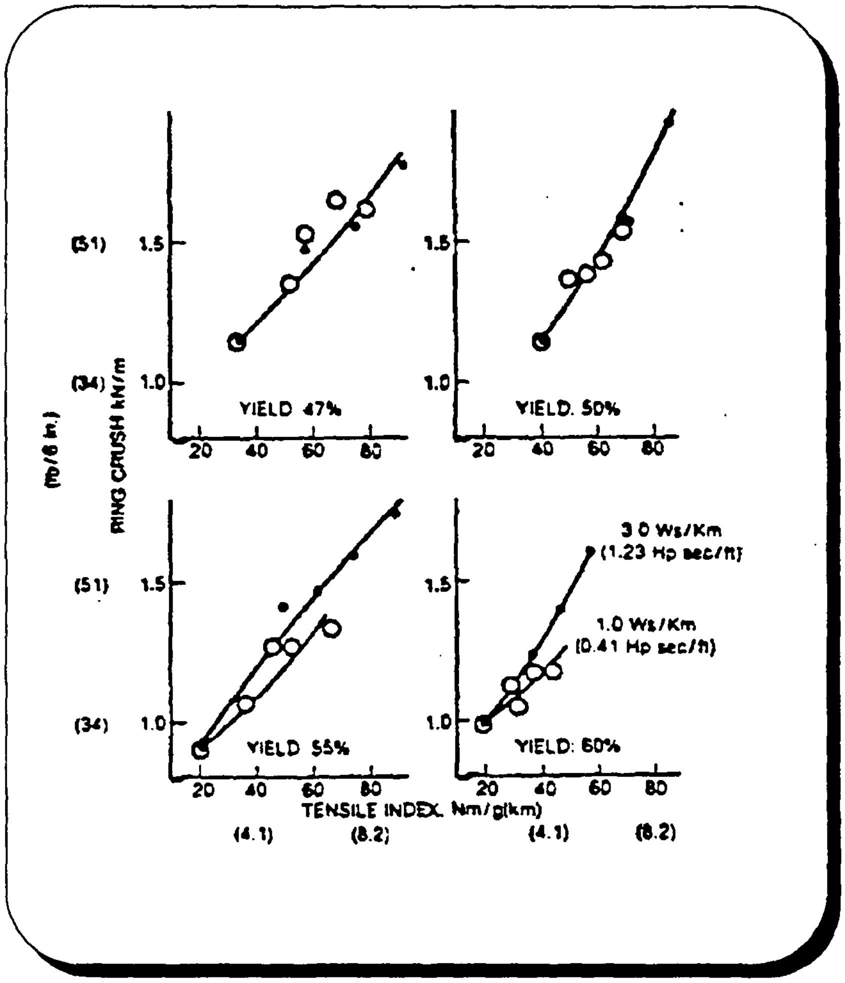

Figure 17. The Effect on the Strength of Sheets Formed from Stocks of Different Consistencies (6).

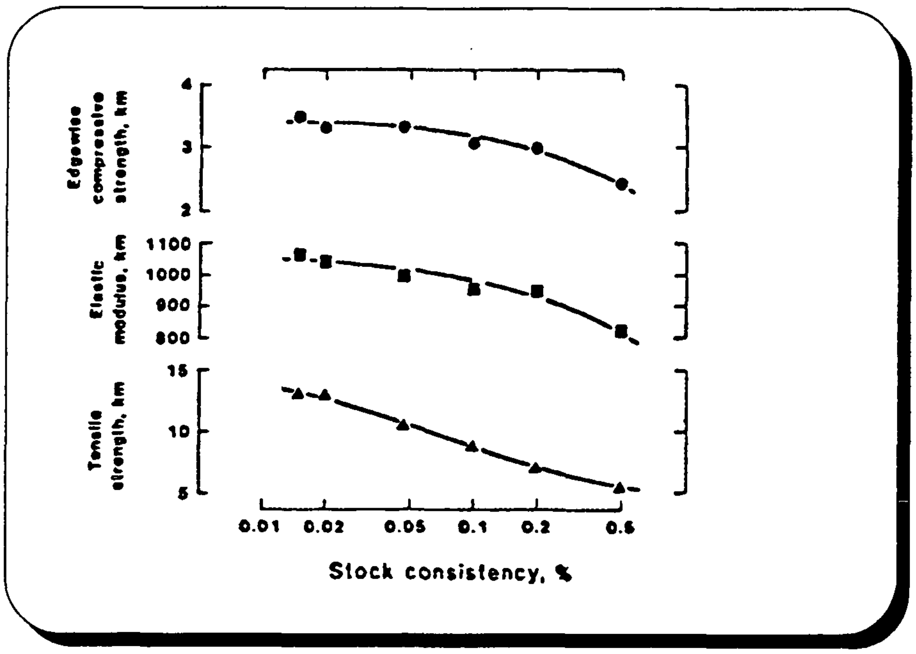

Figure 18. Effect of Jet to Wire Speed Differential on Sheet Anisotropy (29).

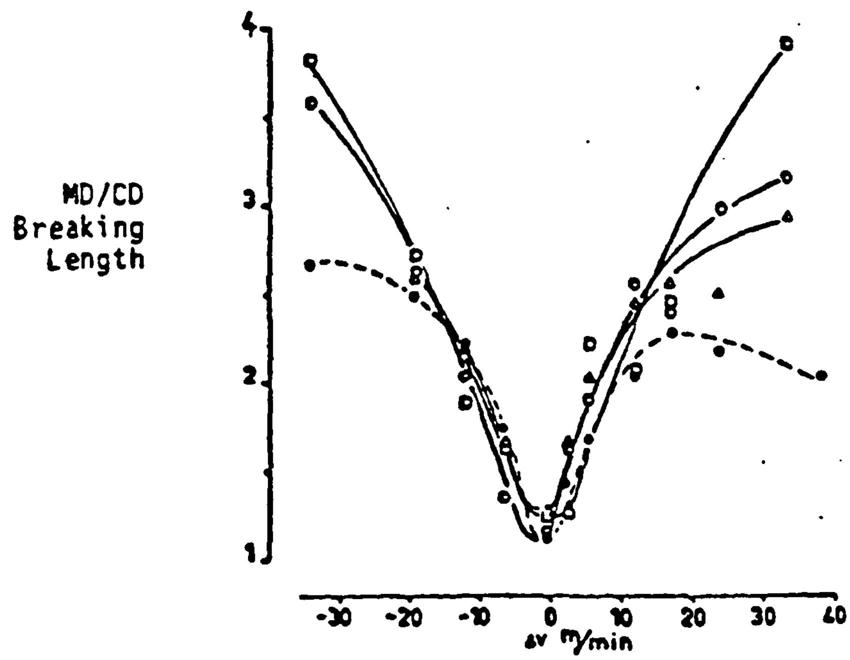

Figure 19. Sheet Properties vs. Different Drynesses out of the Press (9, 22).

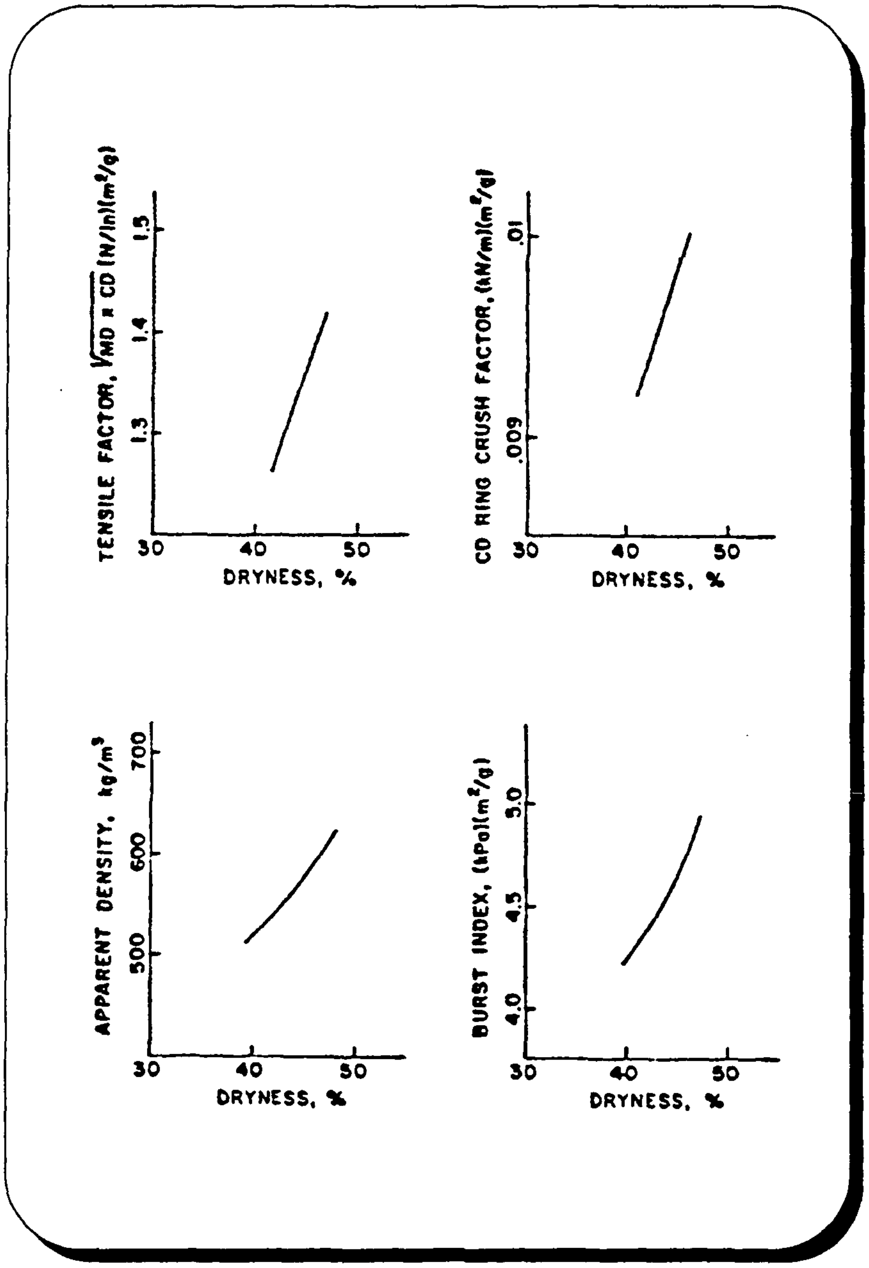

Figure 20. The Effect of Shrinkage on Stress Strain Curve and Modulus of Elasticity (1).

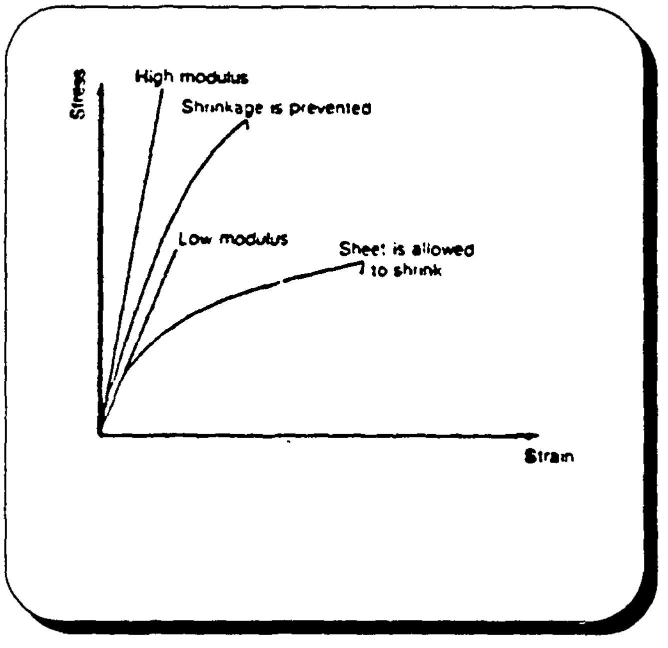

Figure 21. The Effect of Wet Straining on Sheet Density (29).

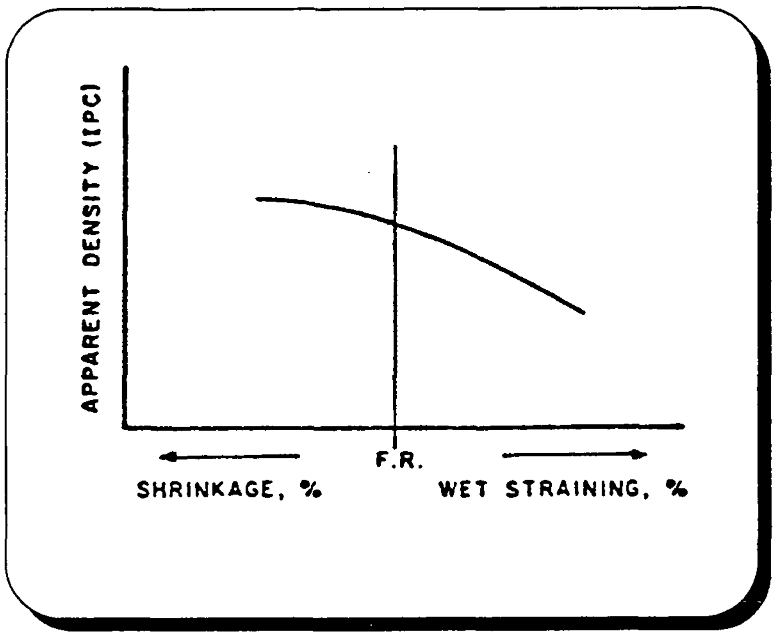

Figure 22. Strain to Failure in Compression vs. Fiber Orientation for Different Drying Conditions (14).

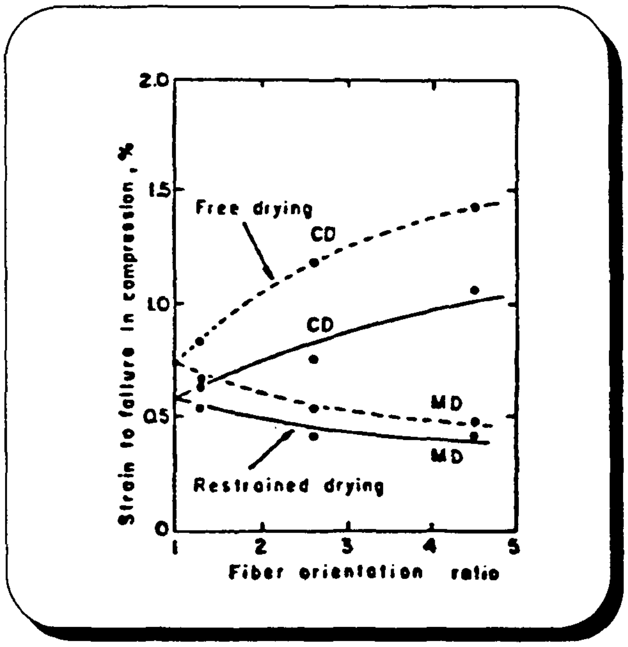

Figure 23.The Effect of Calendering on the Properties of Paperboard (6).

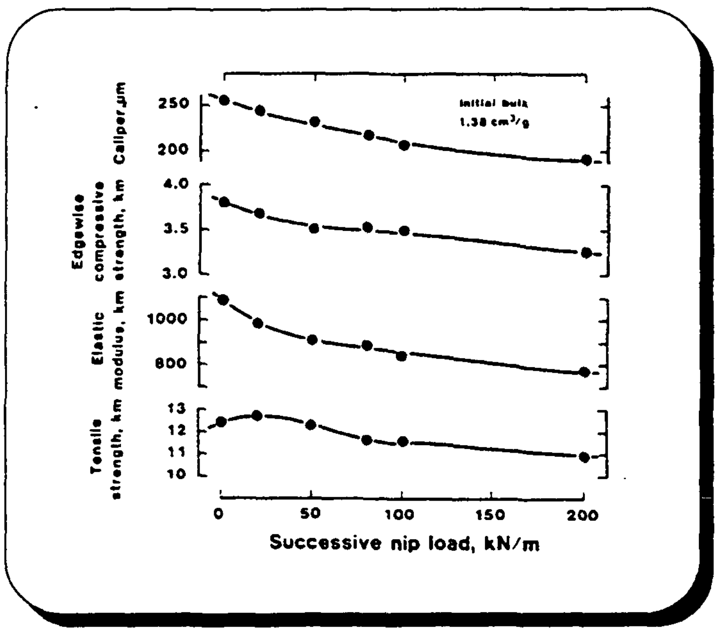

Figure 24. Model for Compressive Properties (23).

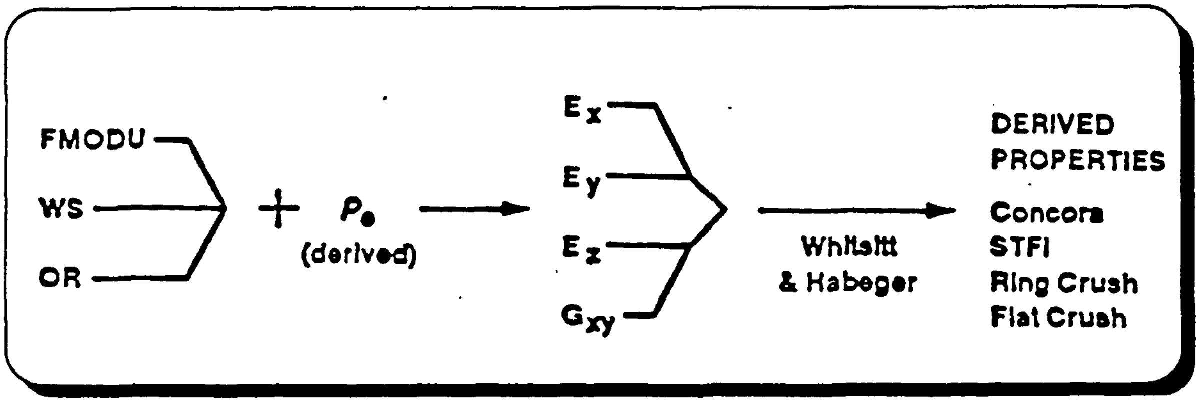


Figure 24. Model for Compressive Properties [23].

Figure 25. Effective Bond Density Development in MAPPS.

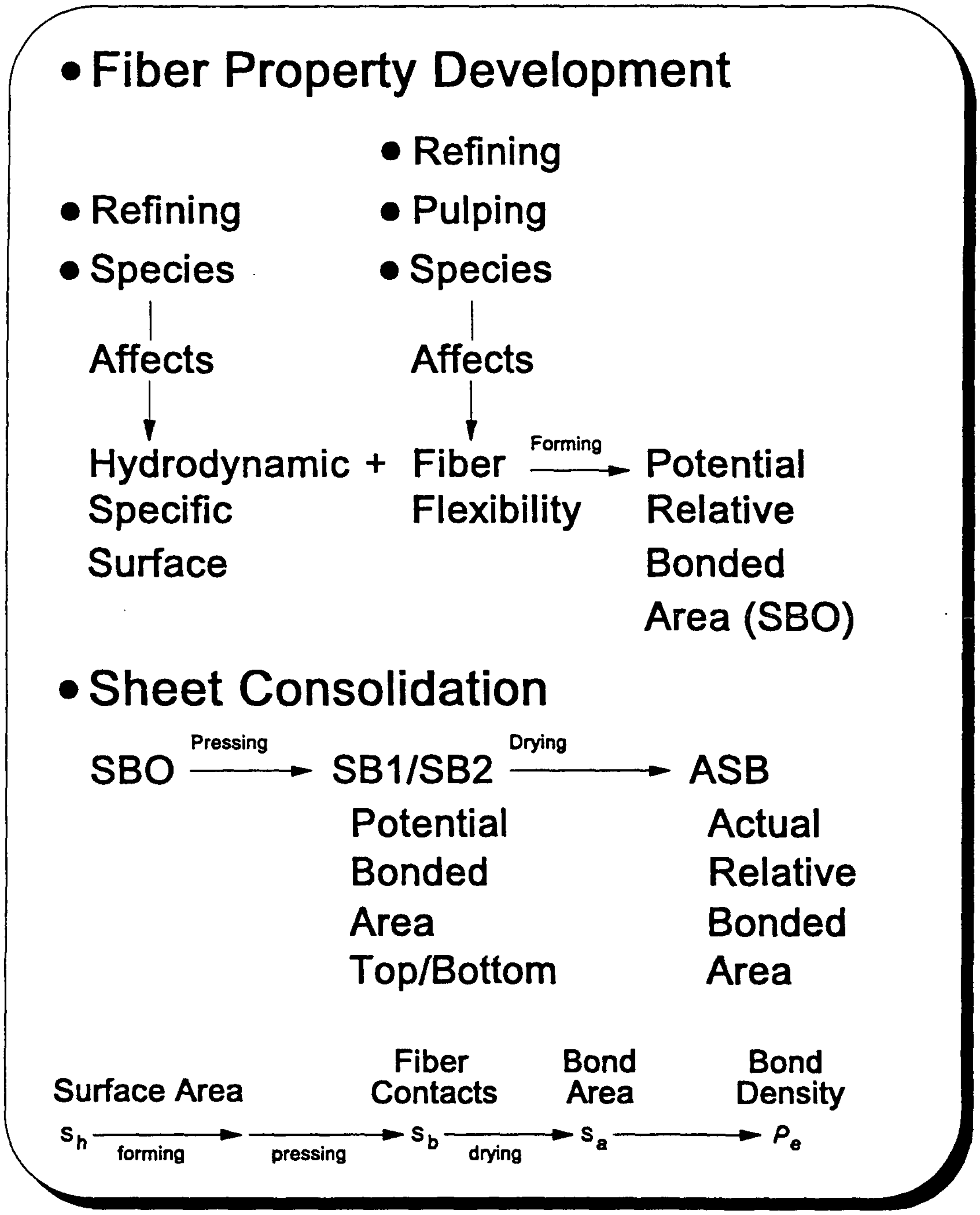

Figure 26. Simulation of a Linerboard Machine, Top Layer.

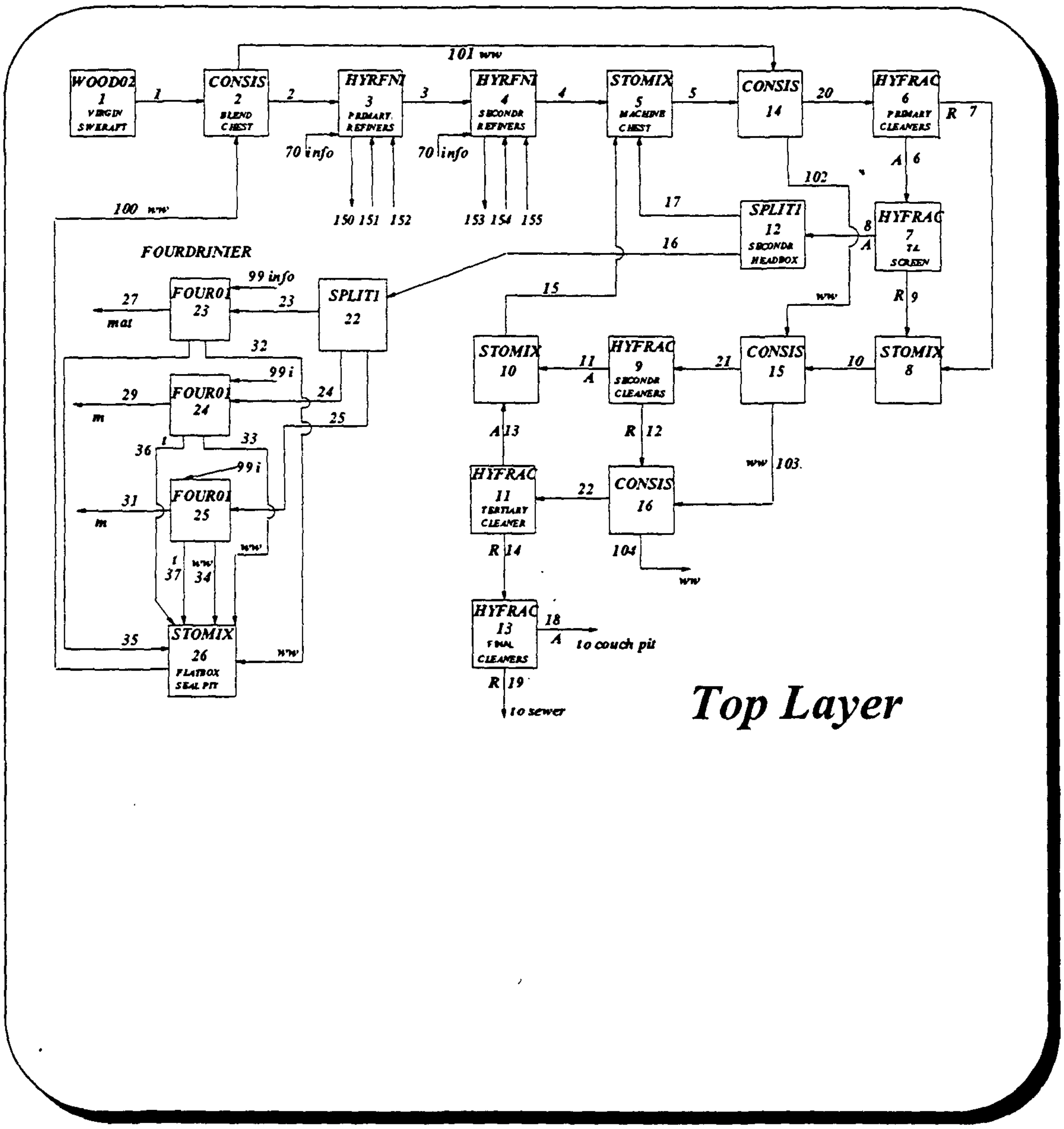

Figure 27. Simulation of a Linerboard Machine, Bottom Layer.

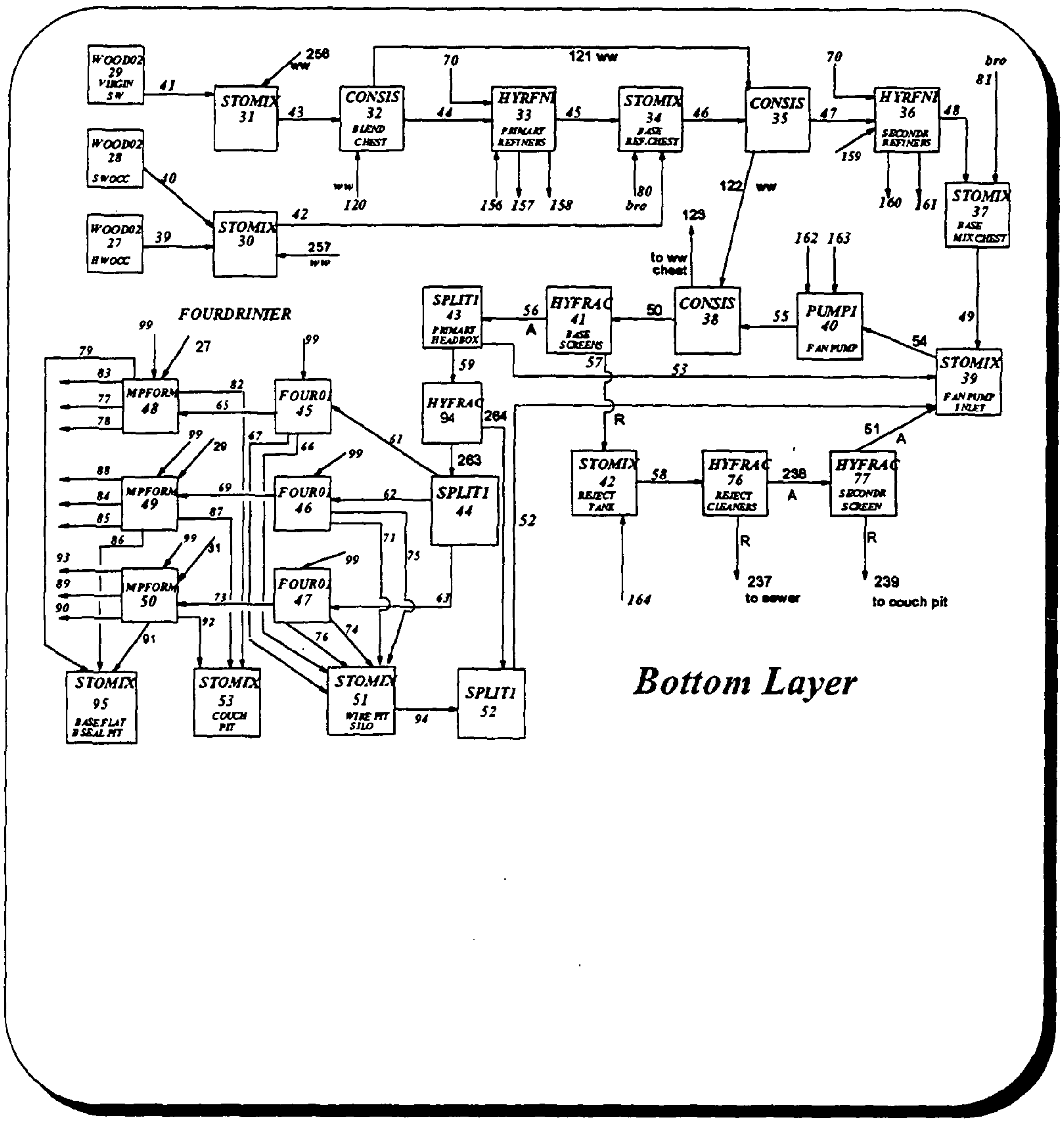

Figure 28. Simulation of Linerboard Machine, Presses, Dryers and Calenders.

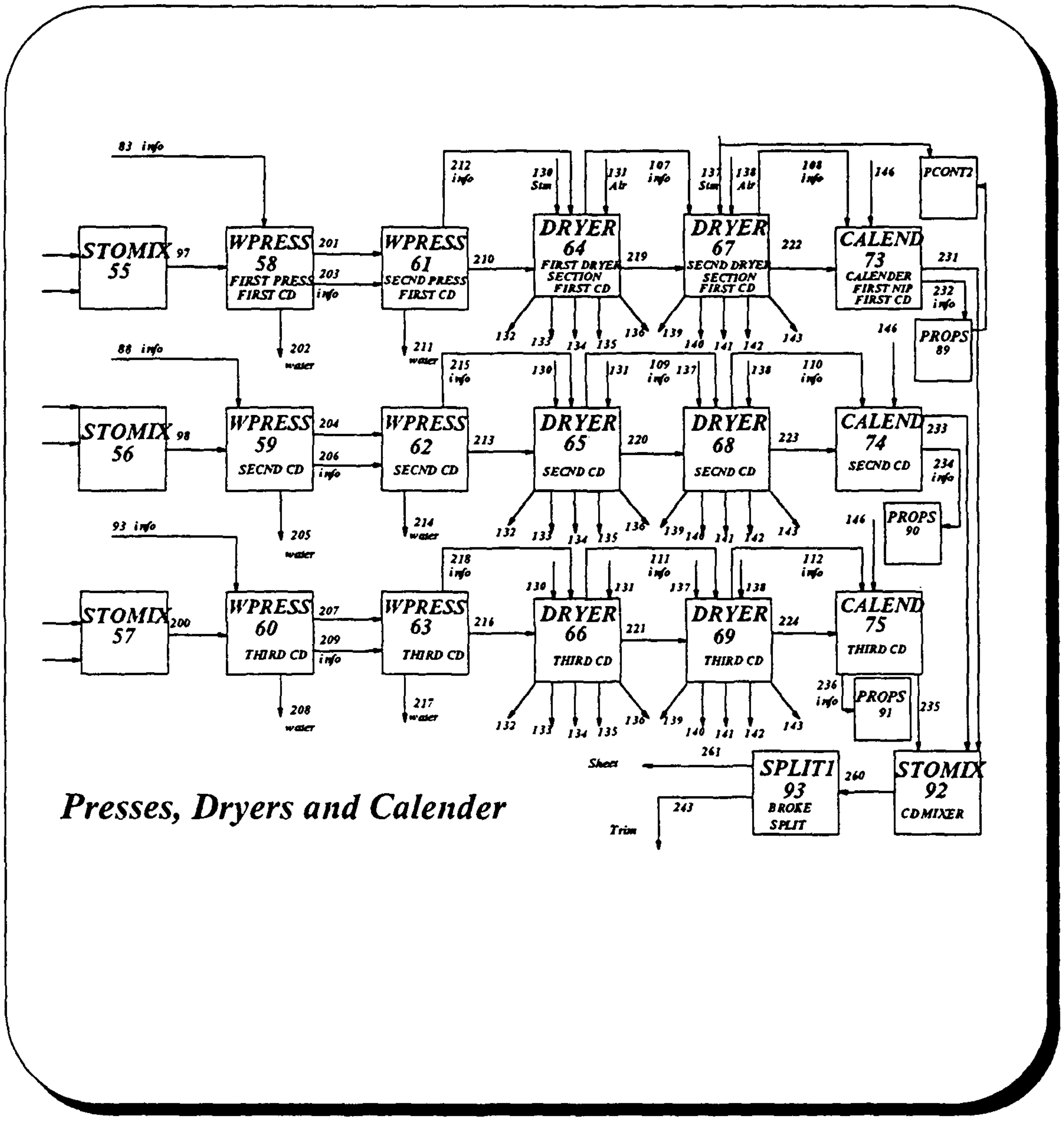

Figure 29. Simulation of a Linerboard Machine, Broke and White Waters.

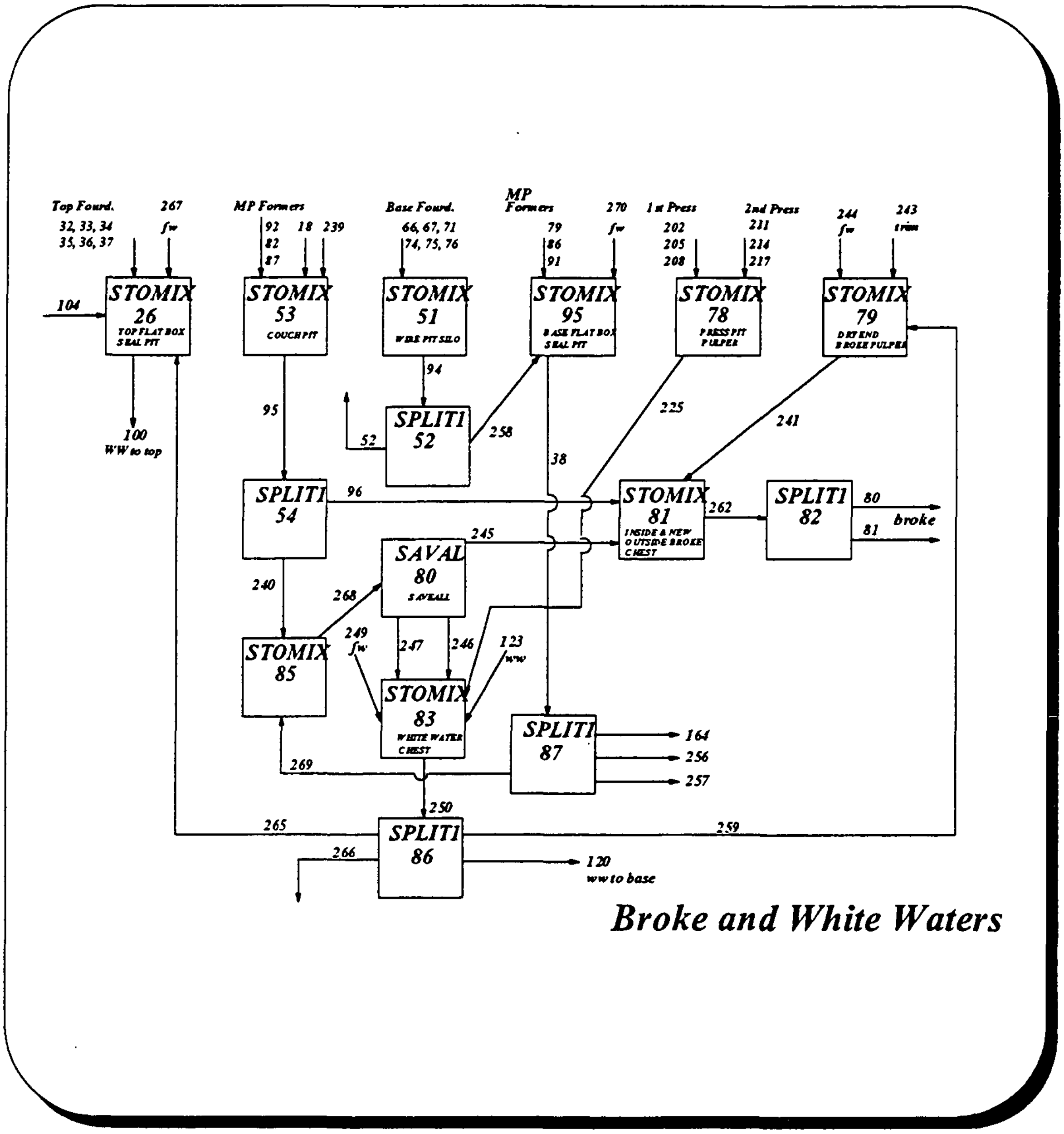

Figure 30. Sensitivity of Burst, Linerboard 69 lb/1000 sq. ft.

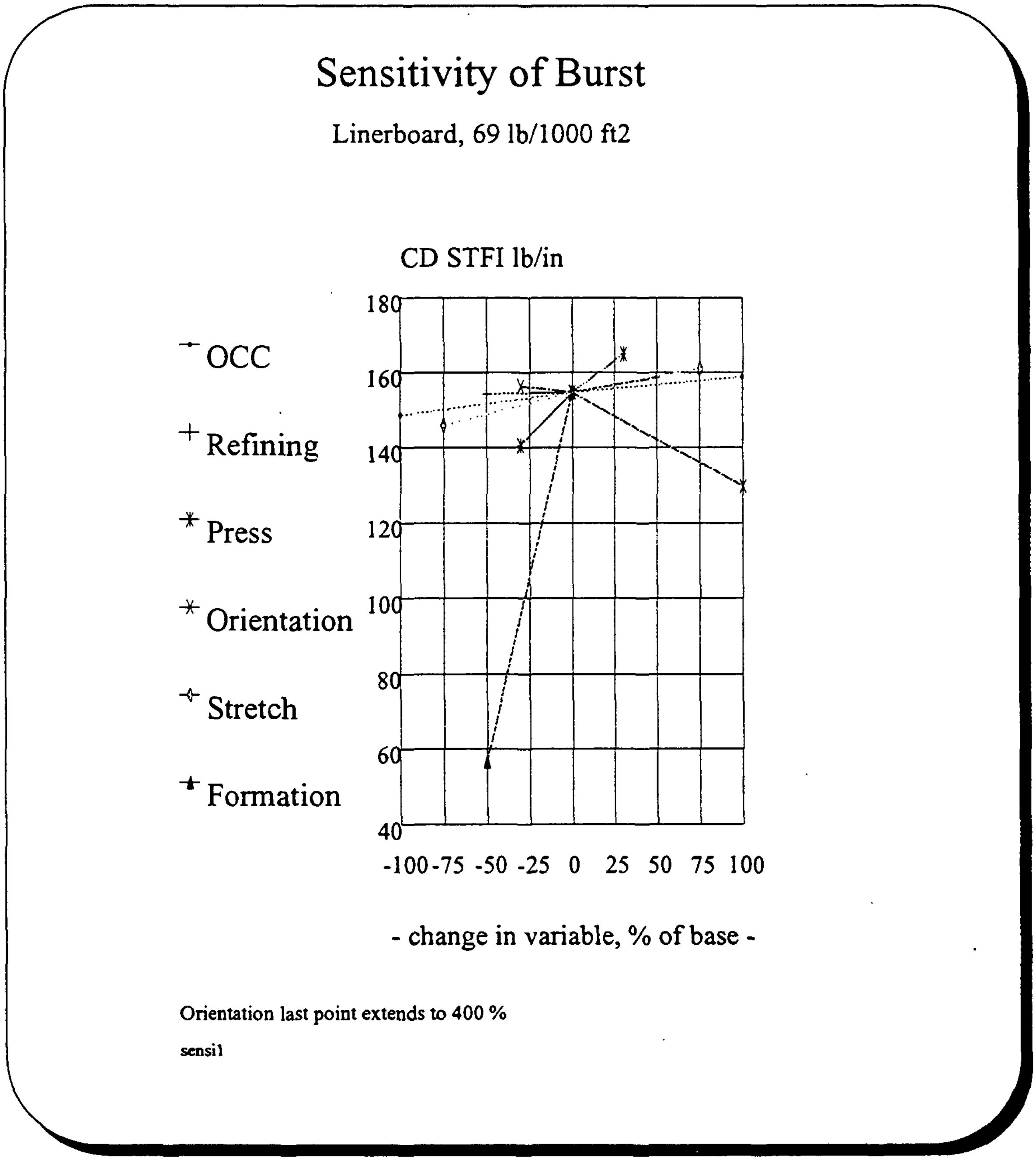

Figure 31. Sensitivity of CD Ring Crush, Linerboard 69 lb/1000 sq. ft.

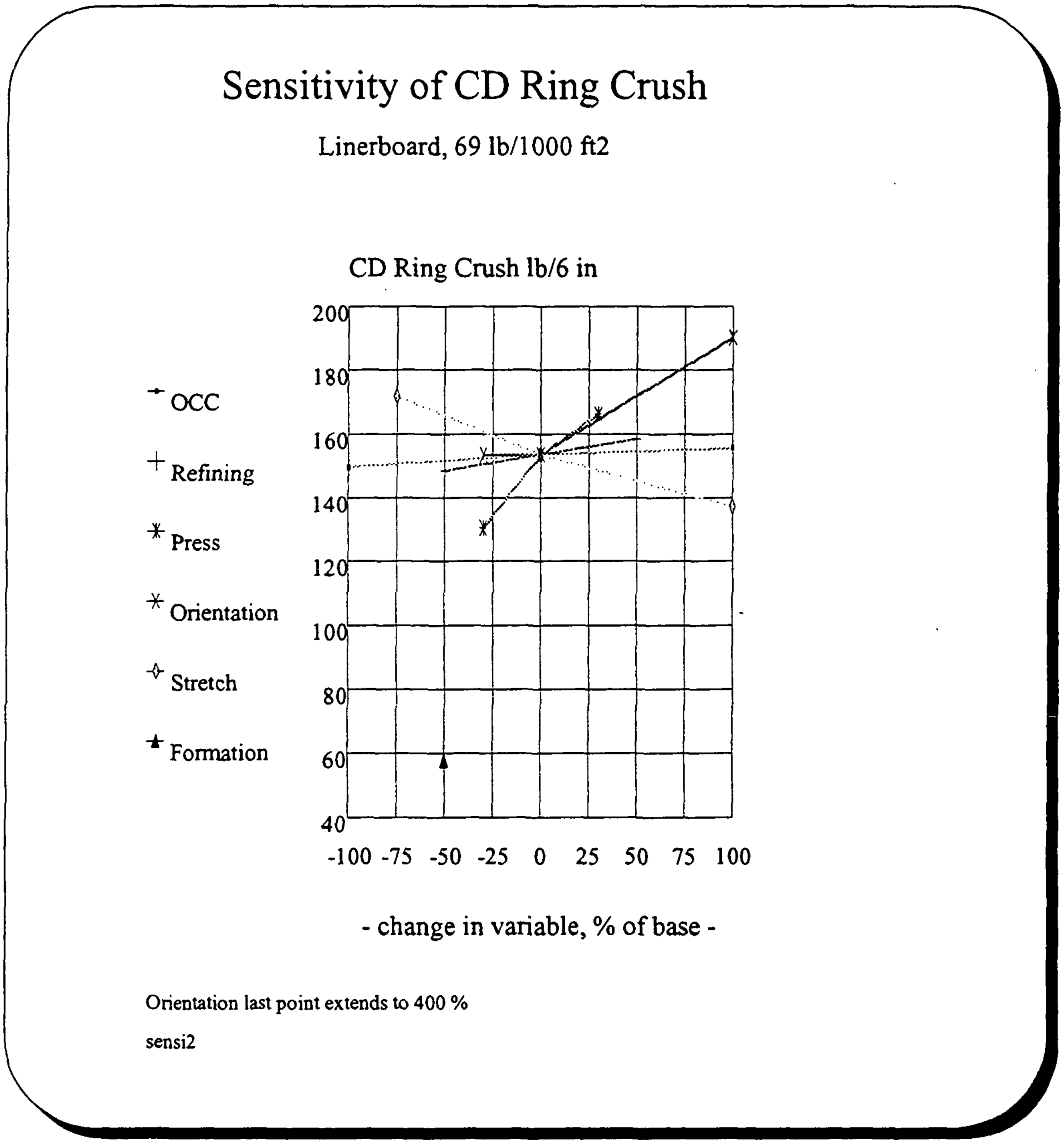

Figure 32. a. Linerboard Compressive Strength vs. OCC Content

CD Ring Crush

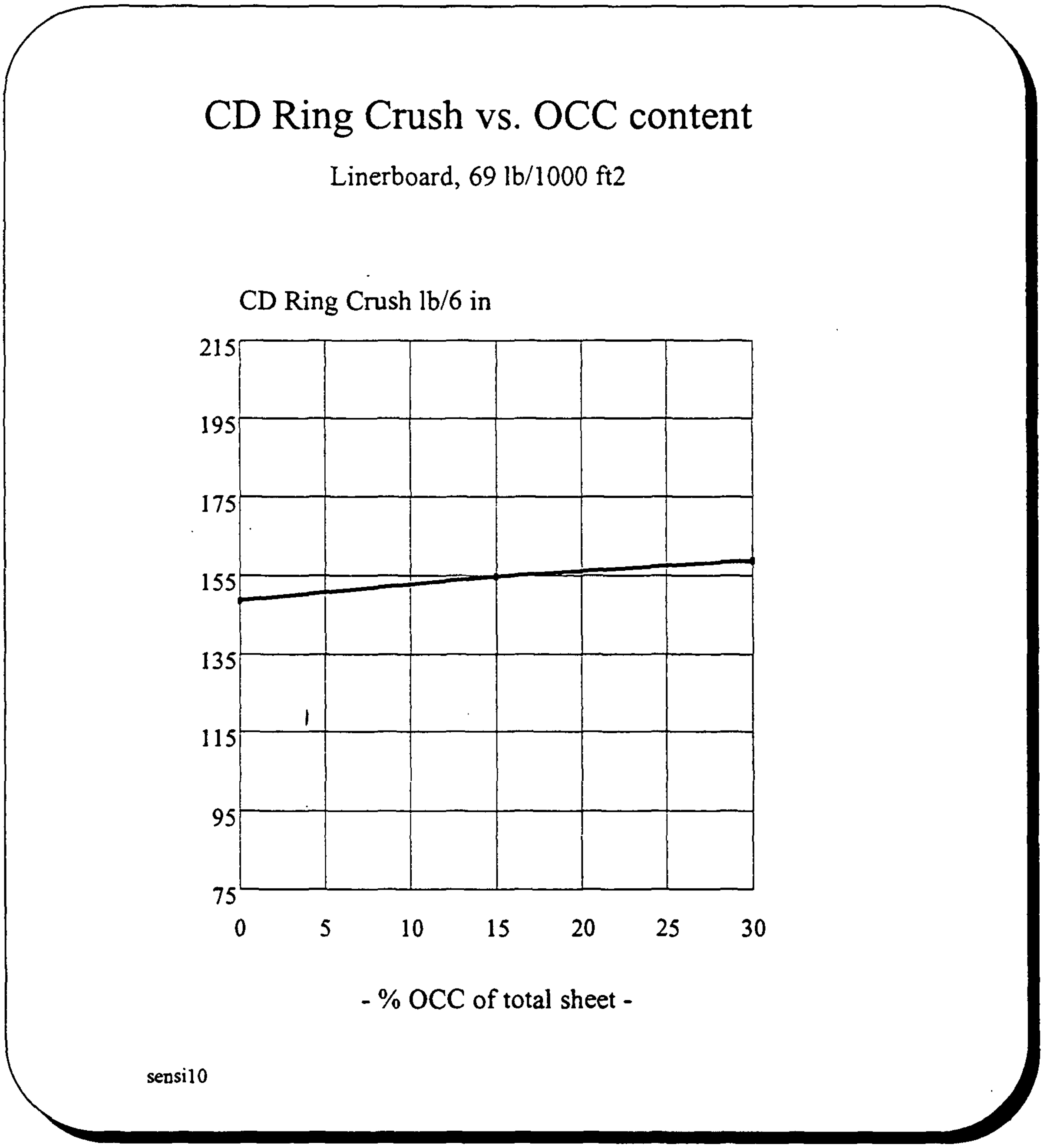

Figure 32 b Linerboard Compressive Strength vs. OCC Content

Burst.

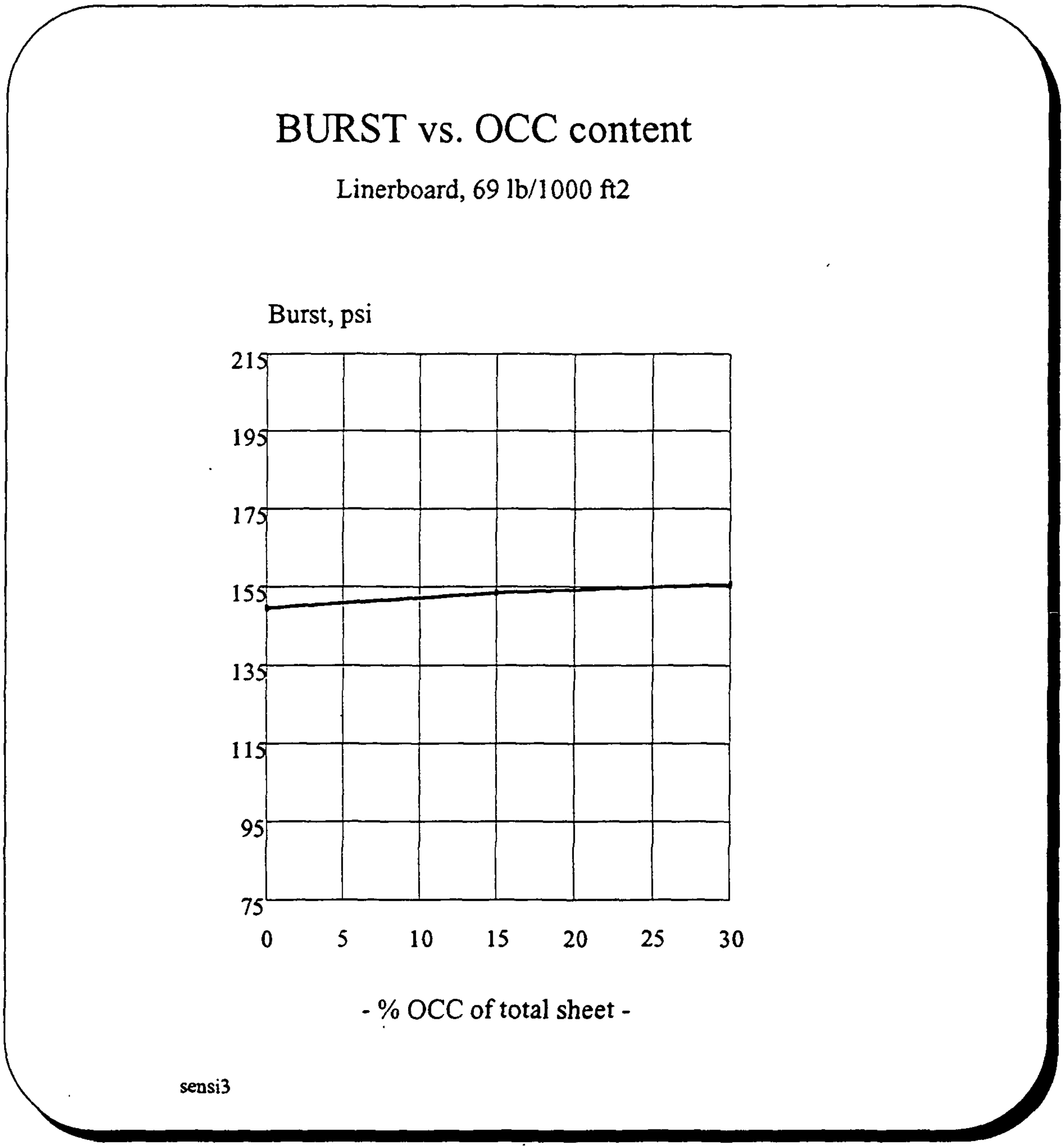

Figure 33 a. Effects of Changes in Refining Power on CD Ring Crush.

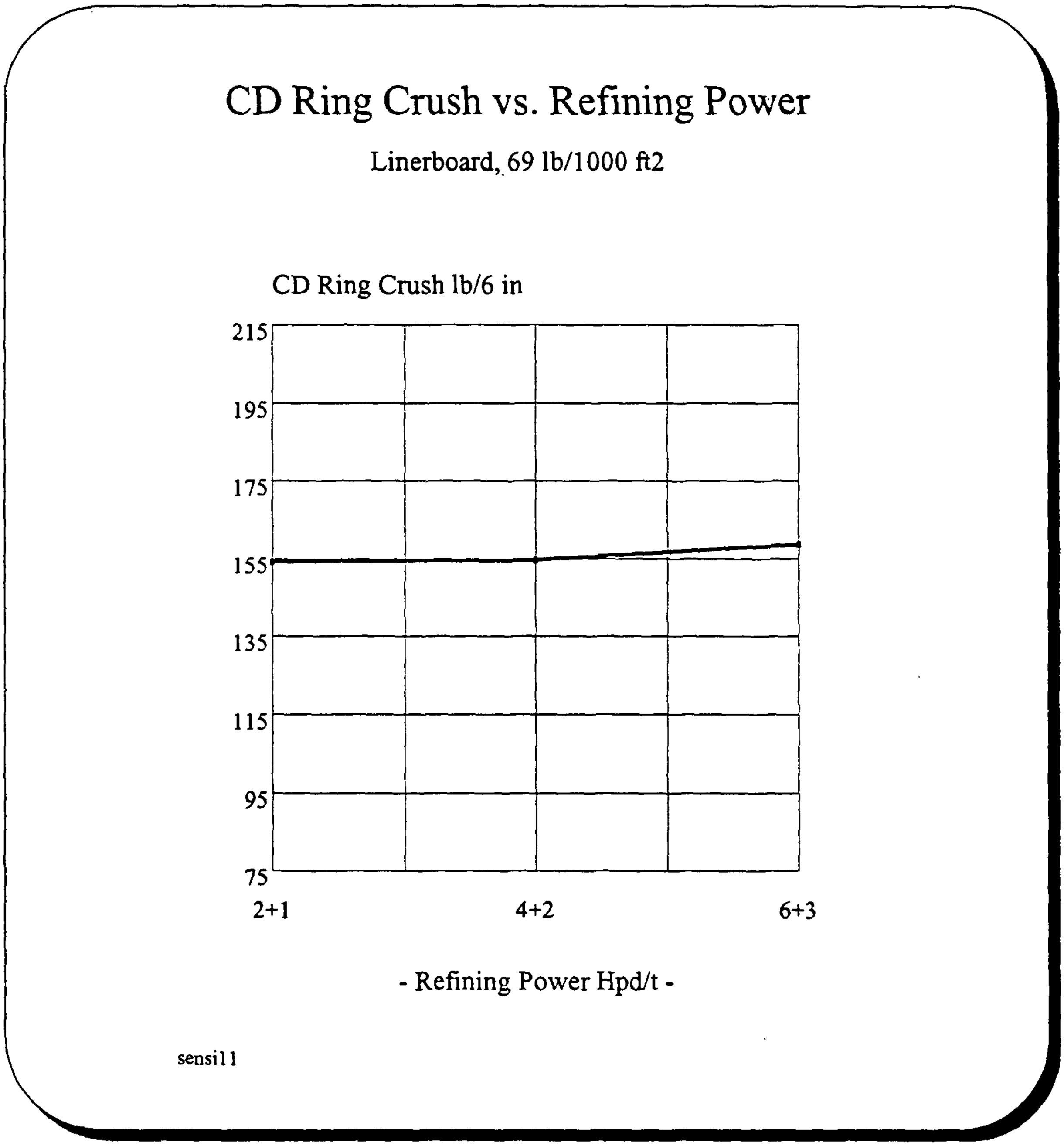

Figure 33 b. Effects of Changes in Refining Power on Burst.

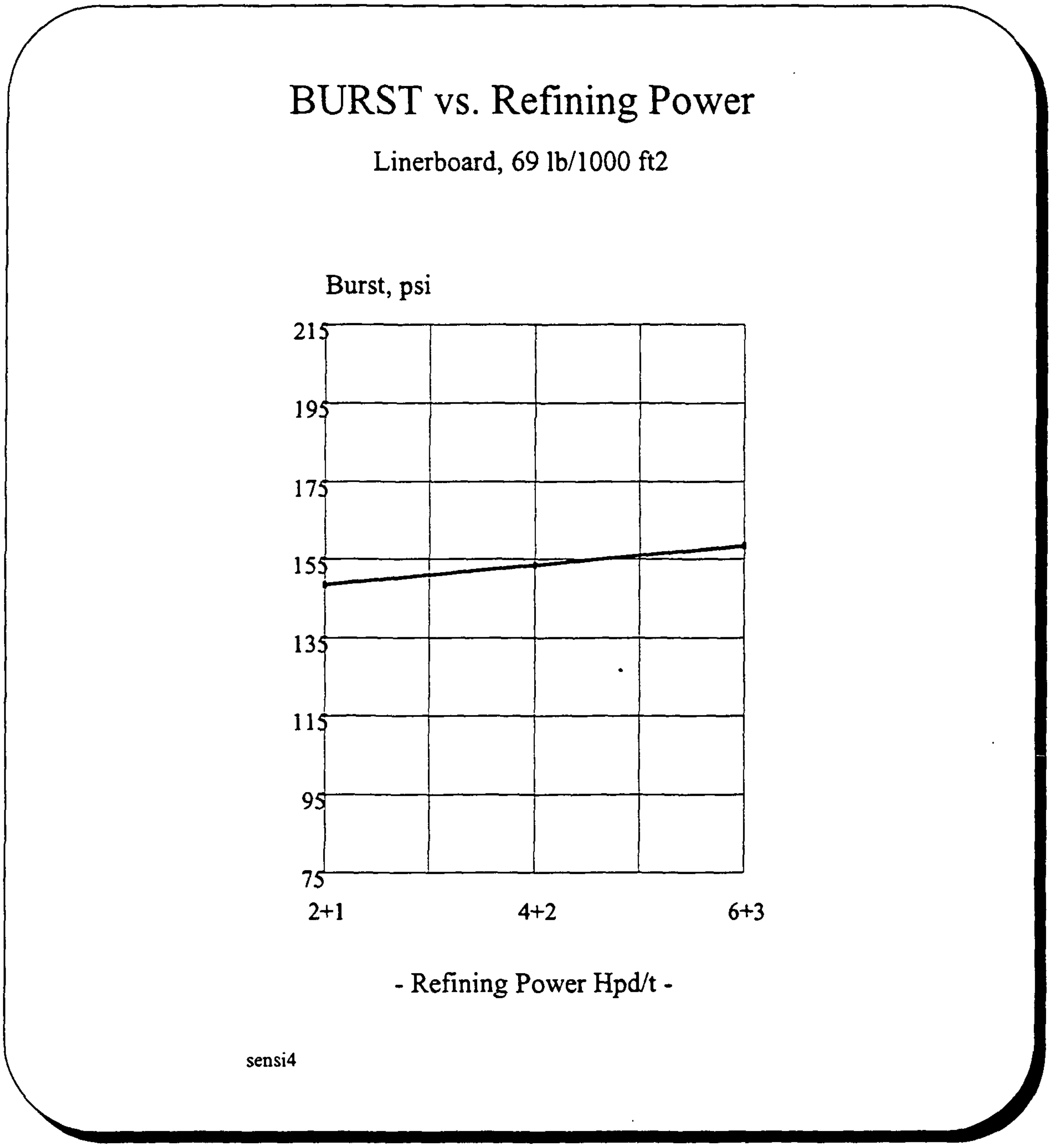

Figure 34 a. Linerboard Compressive Strength vs. Cumulative Press Load (Burst).

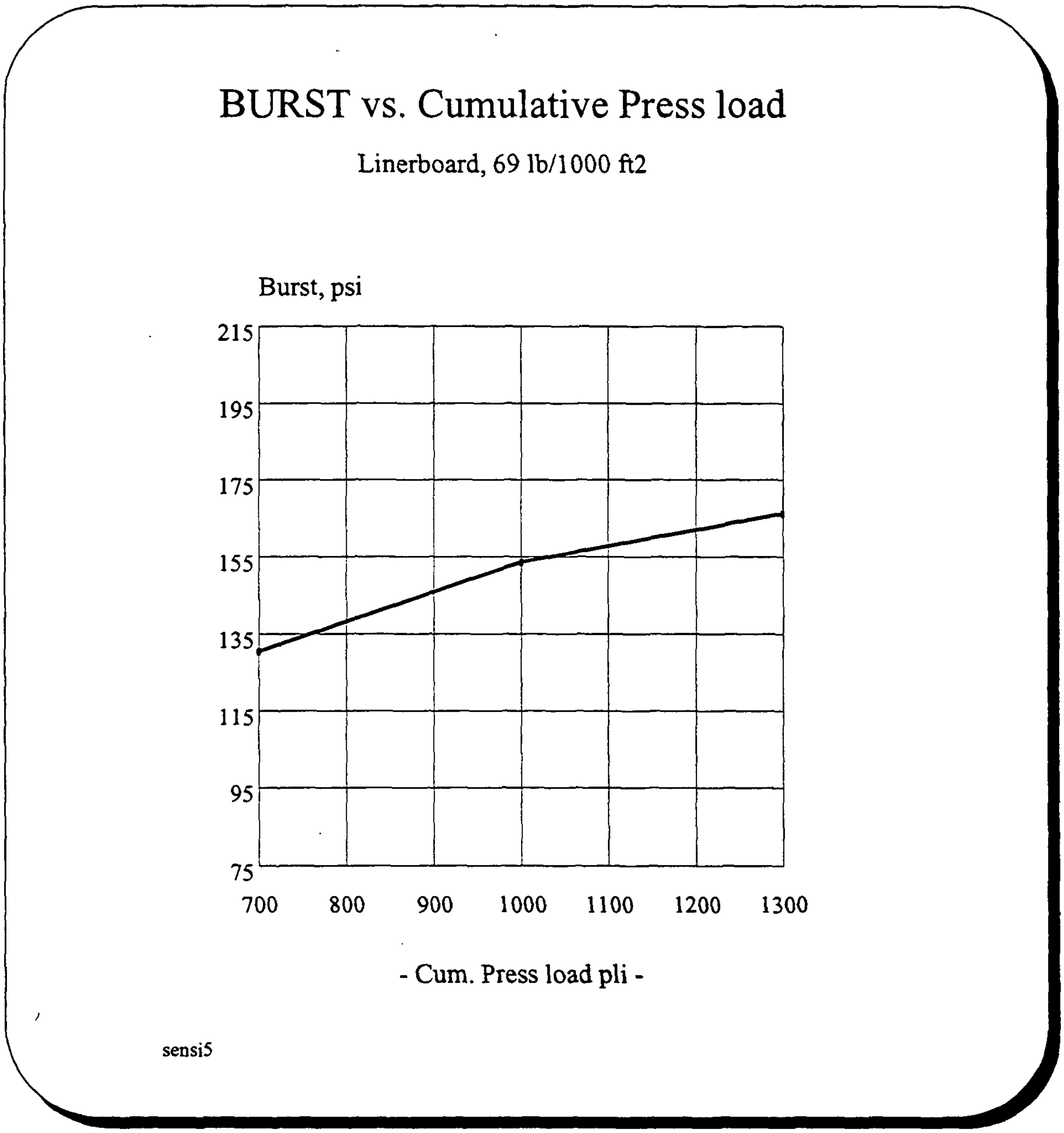

Figure 34 b. Linerboard Compressive Strength vs. Cumulative Press Load (CD Ring Crush).

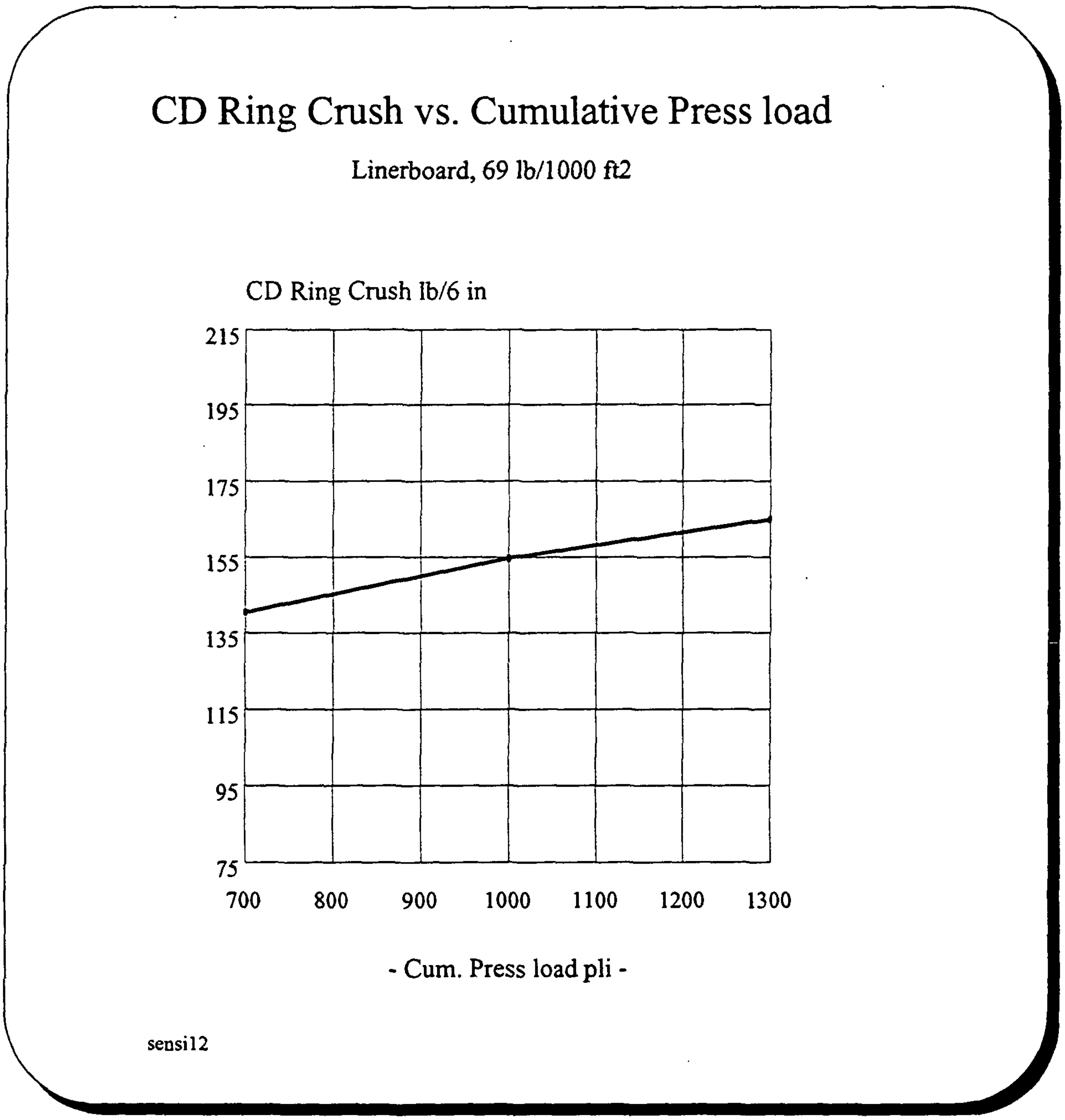

Figure 35 a. Linerboard Compressive Strength vs. Formation (Burst).

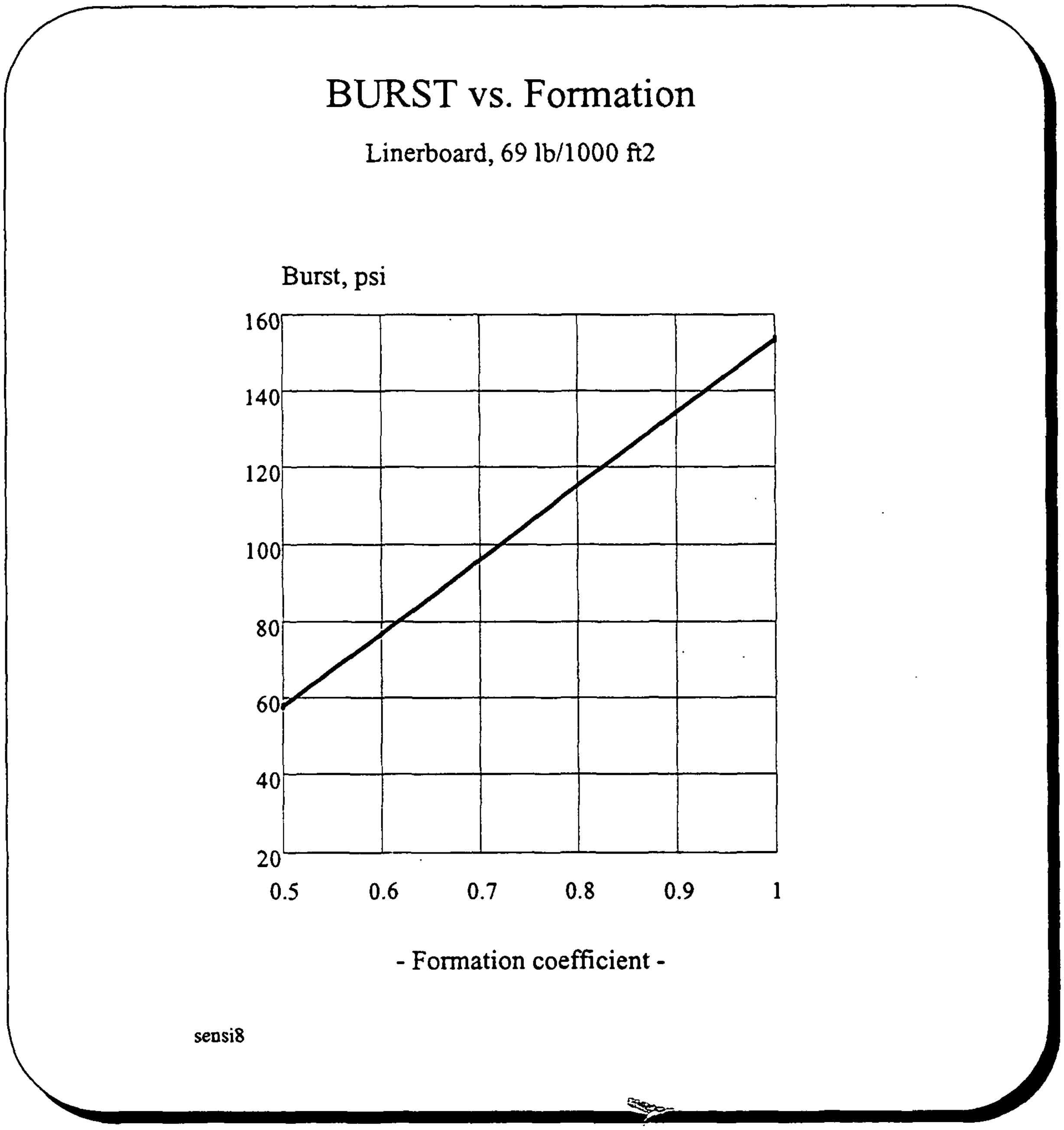

Figure 35 b. Linerboard Compressive vs. Cumulative Press Load (CD Ring Crush).

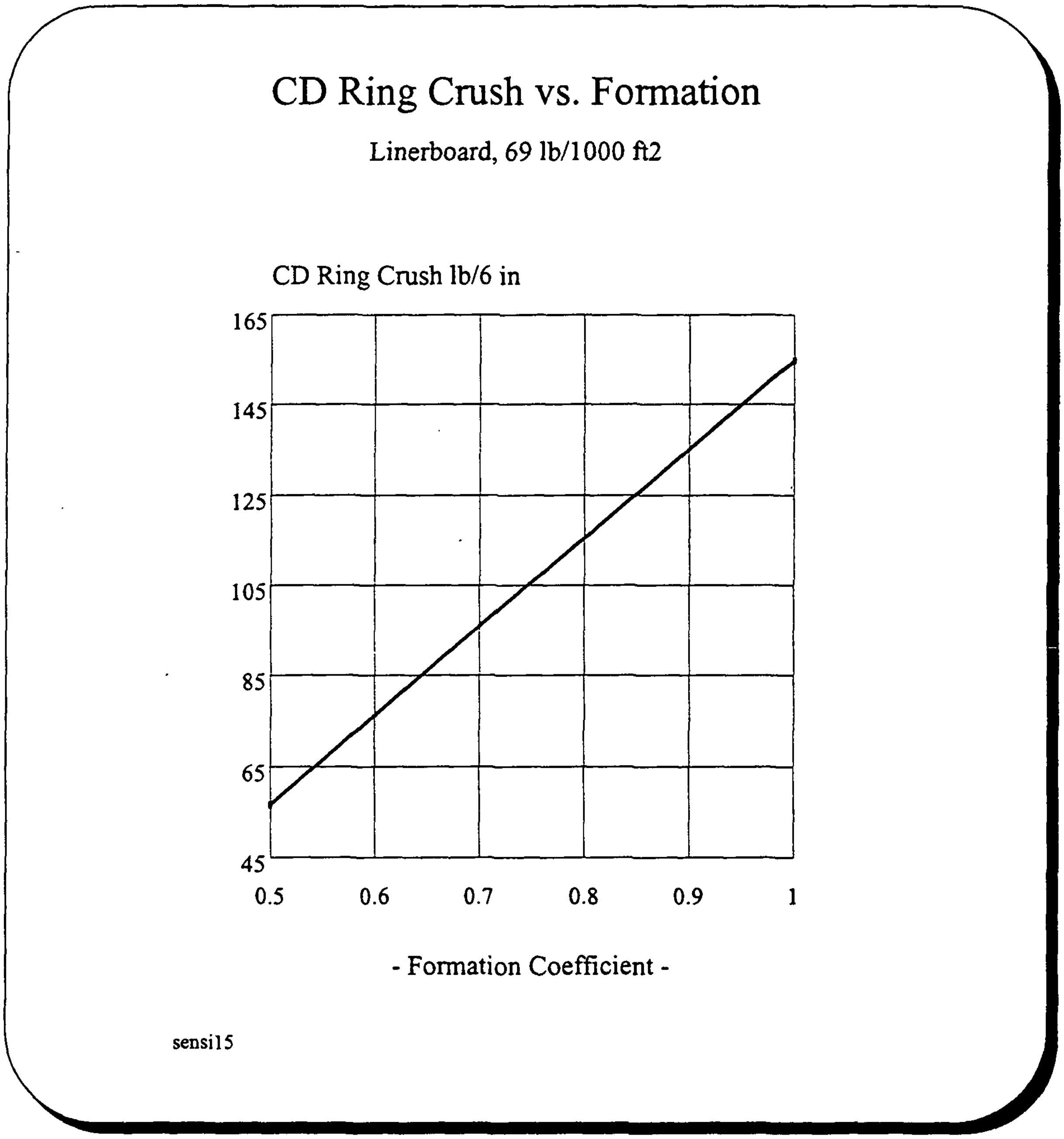

Figure 36 a. Linerboard Compressive Strength vs. Fiber Orientation (Burst).

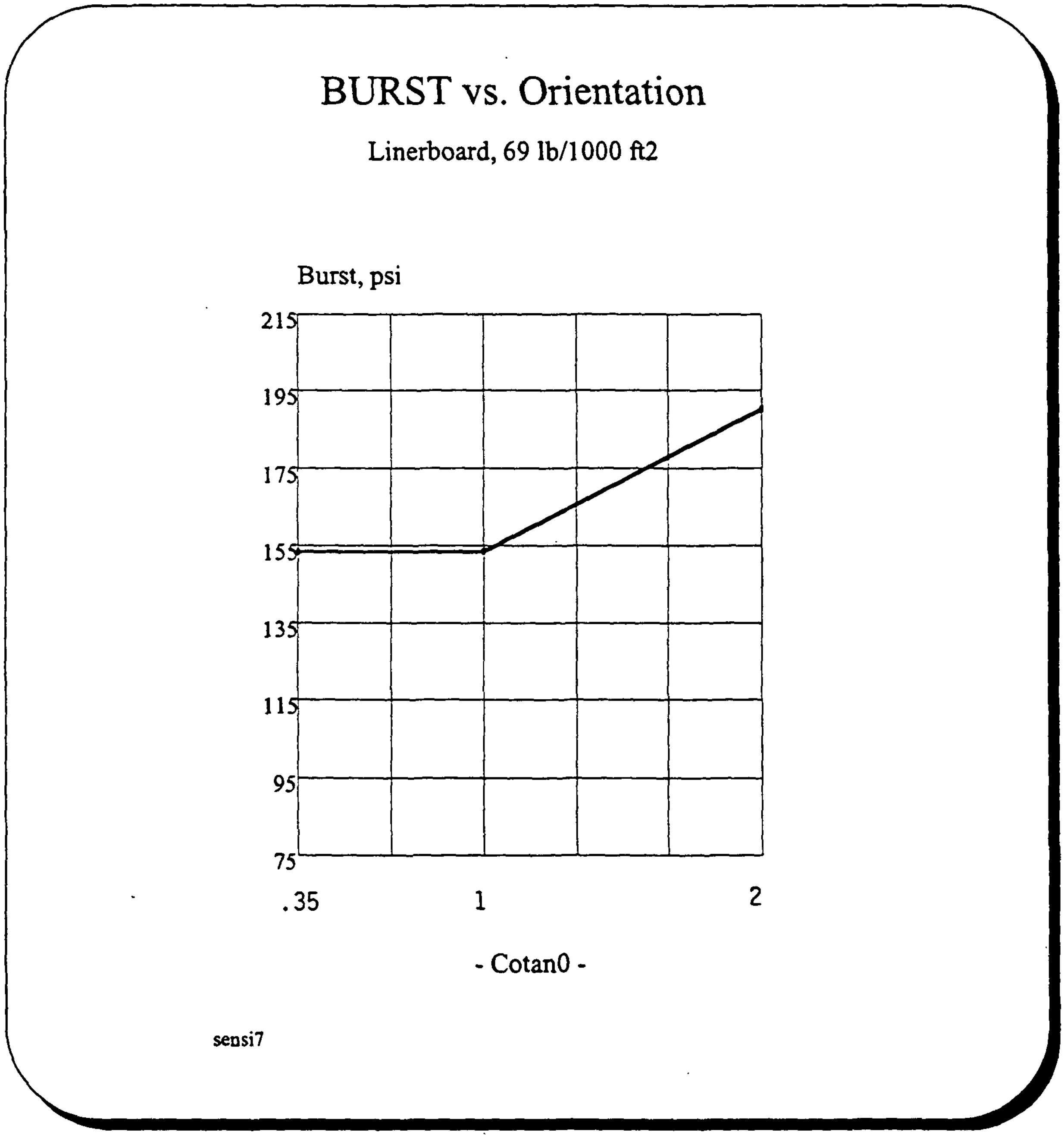

Figure 36 b. Linerboard Compressive Strength vs. Fiber Orienatation (CD Ring Crush).

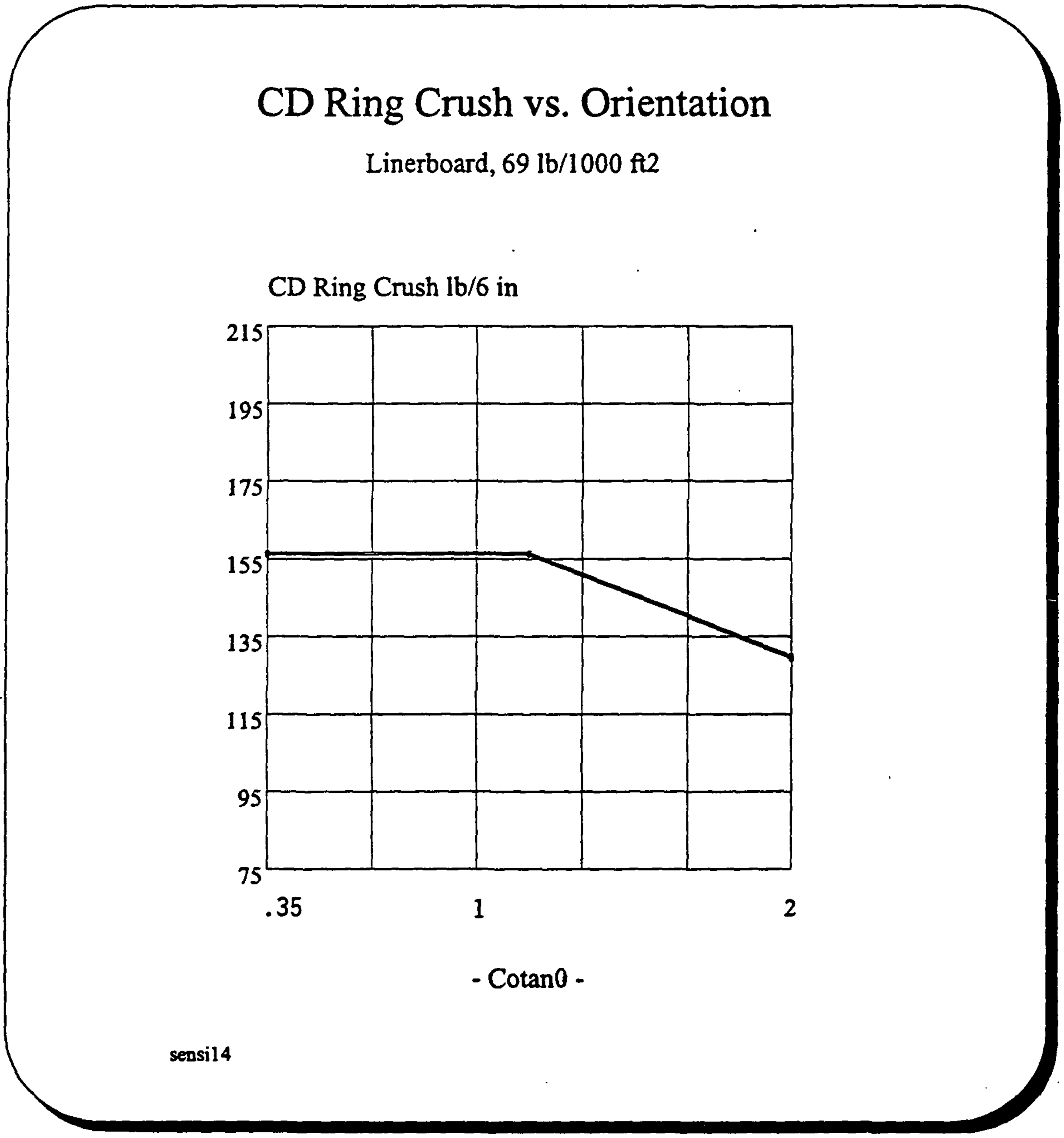

Fig. 37 a. Linerboard Compressive Strength vs. Wet Stretch (Burst)

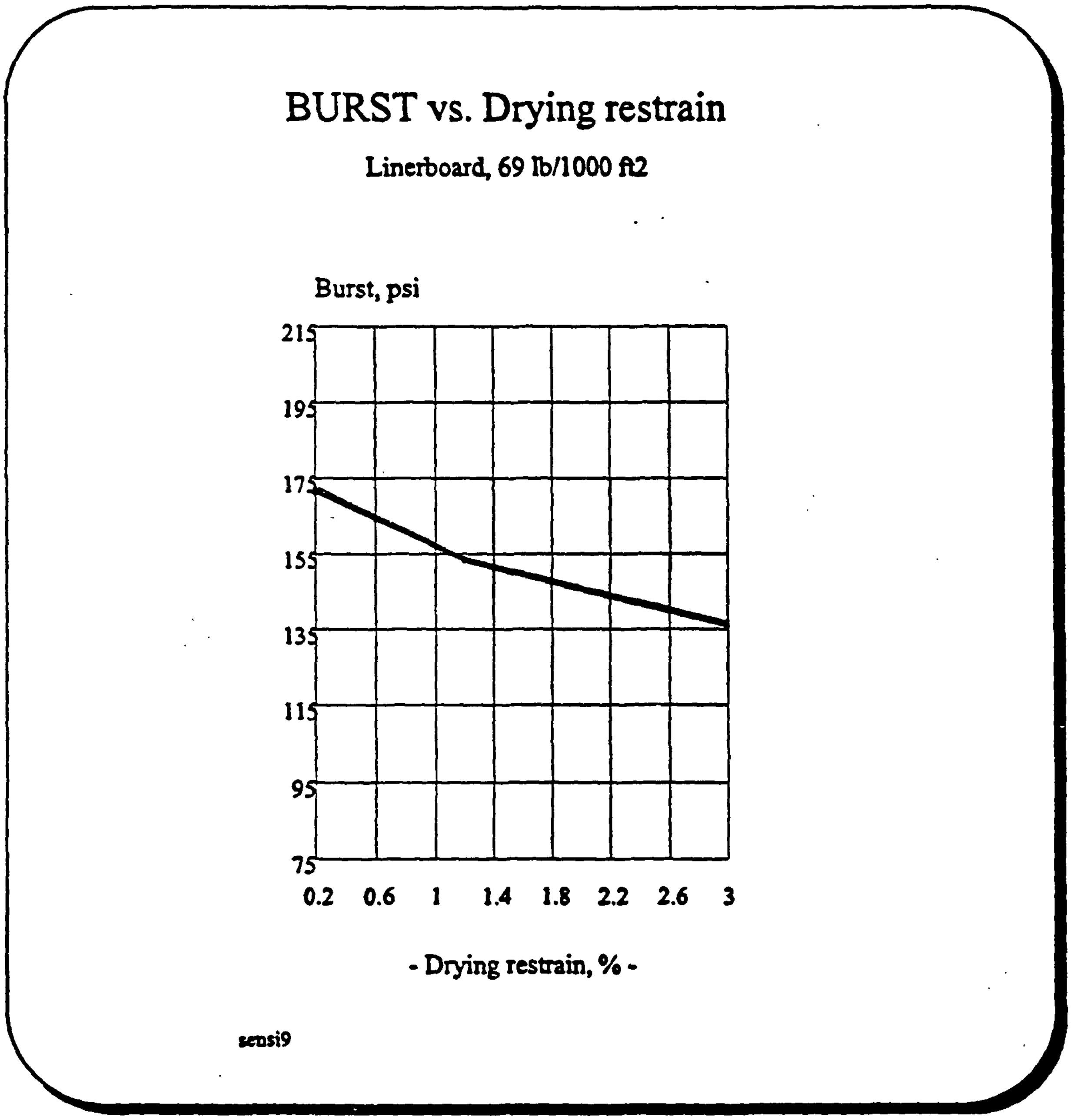

Figure 37 b. Linerboard Compressive Strength vs. Wet Stretch (CD Ring Crush).