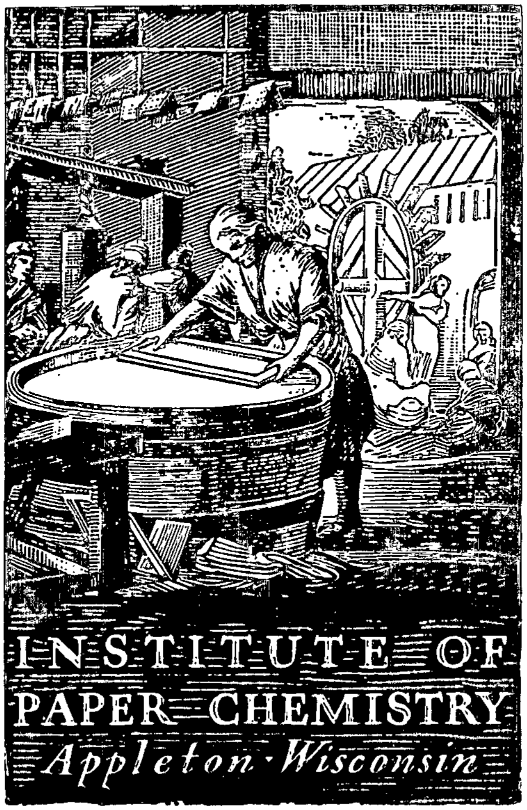

COMPRESSION FAILURE MORPHOLOGY OF LINERBOARD

Project 2695-20

Report Two
A Progress Report
to
FOURDRINIER KRAFT BOARD GROUP
of the
AMERICAN PAPER INSTITUTE

March 15, 1981

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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CONCLUSIONS

This work was directed at obtaining measurements of basic physical properties in order to establish the influence of fiber bonding and fiber stiffness on the compressive strength of handsheets. The results demonstrate that fiber-to-fiber bond strength (as determined by z-direction tensile strength tests) does strongly influence the compressive strength of sheets, especially at the lower levels of bonding. As the bond strength increases, the effect on compression strength reaches a plateau where further increases in z-direction tensile strength do not result in significant increases in sheet compressive strength. Compressive strength does depend strongly on sheet density.

There is no evidence generated by this study that fiber bending stiffness has a significant effect on sheet compressive strength. Even at low levels of bonding, where free fiber length is greatest, the effect of fiber stiffness is hardly noticeable.

While fiber bending stiffness does not seem to be strongly related to sheet compressive strength, free fiber compressive modulus does appear to be related to compressive strength. One of the more interesting facets of this study is measurement of the compressive moduli of elasticity of the pulped fibers. This work is a new contribution. Pulped, undispersed fiber bundles were shaped into columns, aligned, glued onto loading cylinders, and loaded in compression. The load deflection history of the fiber column was recorded. The cross-sectional area of the fiber bundle was determined and the modulus of elasticity in compression was calculated. It is this fiber modulus that correlates well with the sheet compression strength (Table VII).

INTRODUCTION

Box compressive strength is regarded as the chief indicator of the quality of corrugated containers. The compressive strength of the components, liner and medium, play critical roles in the compressive strength of the container. The quality of the corrugated container is dependent on the compressive strength of the linerboard from which it is made.

The goal of this project was to determine the relative importance of fiber stiffness and fiber-to-fiber bond strength in the compressive failure of linerboard. Central to the scheme for determining the role of fiber stiffness and fiber bonding in compressive failure is the development and testing of several sets of handsheets: one of high fiber-to-fiber bonding and high fiber stiffness, one of low fiber bonding and low fiber stiffness, one of high fiber bonding and low fiber stiffness, and one of low fiber bonding and high fiber stiffness.

The program goals require that fiber stiffness and fiber bonding be varied and that these variations be measured. Fiber stiffness is defined as the product of the fiber modulus of elasticity and the fiber area moment of inertia. The fiber modulus was measured in compression on fiber "bundles" prepared from cooked, undispersed chips. The moment of inertia of the fibers within the handsheets was determined by sectioning the sheets, photographing the sections under magnification and then calculating the moment of inertia from dimensional measurements of the photograph. Fiber-to-fiber bonding can be varied by changing the press drying pressure applied to the wet sheets. The fiber bond strength was measured by means of the z-direction tensile test, and bonded area was determined in terms of relative bonded area using a gas absorption technique. Fiber stiffness can be varied by using thin wall earlywood or thick wall latewood fibers in the preparation of the handsheets. The influence of these parameters on compression was determined by plotting the compressive strength _vs._ fiber bonding and compressive strength _vs._ fiber stiffness.

BACKGROUND

Compressive performance is generally accepted as the best criterion of corrugated box quality even though the regulatory requirements specify quality in terms of the bursting strength of the combined board. Box compression is dependent on a number of factors - e.g., box dimensions, combined board geometry, environmental conditions, type commodity, strength of the adhesive, workmanship, type and grade weight of components and quality of components. The quality of the components plays a major role in determining the potential compression performance of the box. Therefore, in order to optimize the quality of the corrugated board components to allow the most efficient box performance, it is imperative to know the primary characteristics of the linerboard which contribute to box compression and the mechanism which triggers failure of the liner when the box is subjected to a compressive stress.

Post-failure examination of the compressive failure zone of linerboard yields evidence that the mode of failure may involve bond breakage (delamination), fiber buckling or a combination of these two. This concept is supported by earlier work at IPC (1). When the maximum compression strength is plotted against z-direction tensile strength of paperboard, the resulting curve exhibits essentially two major slopes (Fig. 1). Below a z-direction tensile strength of about 11 kg/cm^2, maximum sheet compression increases greatly with z-direction tensile; above 11 kg/cm^2 there is only a mild increase in sheet compressive strength. It may be inferred from this that bonding plays a major role in the early development of compressive strength and that some other factor, such as stiffness of the fiber segments, becomes important after a critical level of bonding has been obtained.

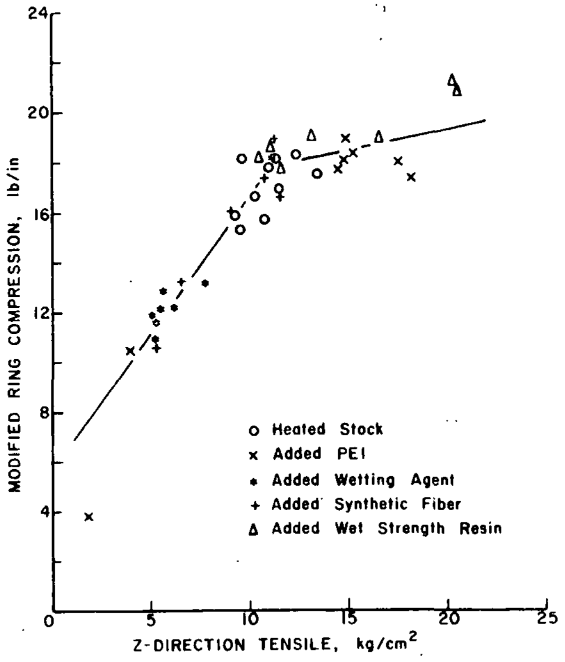

Figure 1. Relationship Between z-Direction Tensile Strength and Modified Ring Compression

Koning and Haskell (2) evaluated the effect of various papermaking factors on the compressive strength of linerboard. Factors investigated included wood species, pulp yield, refining, wet-pressing pressure, and sheet surface properties. Two of these factors, wet-pressing pressure and refining, had a significant effect on compressive strength. Pulps refined to 450 CSF had higher compressive strength than pulps refined to 600 units. This trend held true for every pulp yield and for every method of refining. Handsheets from pulps refined to 450 CSF and wet-pressed at 160 lb/inch^2 had a higher compressive strength than sheets wet-pressed at 40 lb/inch^2. This same trend occurred with the pulp refined to 600 CSF; handsheets wet-pressed at 160 lb/inch^2 had a higher compression strength than sheets wet-pressed at 40 lb/inch^2. Both of these factors, wet-pressing and freeness, should increase the bonded area. On the other hand, an increase in refining could result in some fiber damage and a possible lower intrinsic fiber stiffness. A decrease in the stiffness of the individual fibers might be expected to decrease sheet compressive strength.

Seth, Soszynski and Page (3) conducted a series of experiments in which they varied wet pressing pressure and measured the resulting compressive strength in the handsheets. They found that the compressive strength of the handsheets reached a plateau at the high levels of wet pressing pressure. They concluded that fiber bonding controlled the compressive strength of the handsheet at low levels of bonding, and that the compressive strength of the fibers controlled the compressive strength of the sheets at high bond strengths. There have been no measurements of the compressive strength of single wood fibers.

deRuvo et al. (4) investigated the compressive behavior of paper, the static ultimate load, the creep to failure under constant load, stress relaxation, and modulus changes during loading cycles. It was observed that tensile strength was 2 or 3 times the compression strength, that paper in compression relaxes at a higher rate than in tension, and the rate of deformation during creep is higher in compression than in tension. It was postulated that two different mechanisms would control compressive failure. For low density sheets, failure is ascribed to buckling of the fiber segments. For high density sheets, the compressive strength is assumed to be governed by the shear modulus of the matrix composed of the mixture of hemicellulose and lignin.

Thus, there are three probable causes for compression failure identified in the literature: bond failure, fiber buckling, and compressive failure of fibers themselves. This project addresses the first two causes, bond failure, and fiber buckling.

MEASUREMENT OF VARIABLES

Handsheets with the desired range of bonded area, bond strength, and fiber stiffness were prepared. There are two methods in common use for the measurement of the relative bonded area (RBA), the optical and gas absorption techniques. The optical method is based on the assumption that the fiber area which is involved in interfiber bonding does not scatter light and that the unbonded area will scatter light. Haselton (5) has shown that the specific scattering coefficient of handsheets can be related to the bonded area. The optical method has the advantage of being quick and nondestructive. However, because the handsheets used in this investigation were heavy weight, unbleached sheets, the optical method could not be used. The gas adsorption method was used in this study to determine RBA. In this technique the gas (N_2) is assumed to be adsorbed on the unbonded fiber areas but not adsorbed on the areas involved in fiber-to-fiber bonding.

There is no completely acceptable method for measuring intrinsic bond strength although the test method usually associated with bond strength is the z-directional tensile test (ZDT). It is a straightforward technique that has been used by industry for some time. The two surfaces of a paper specimen are fastened to metal cylinders with double sided tape and the cylinders are attached to the jaws of a tensile testing machine. A transverse load is applied to the specimen and the load per unit area required to cause the specimen to separate and fail is determined. One objection to the z-directional test is that the interfiber bonds are loaded in tension normal to the plane of the bond whereas, in the case of a sheet loaded in compression or tension in the plane of the sheet, the interfiber bonds would be loaded in shear.

In this work, a ZDT test, as modified by Wink and Van Eperen (6) was used to measure bond strength. The specimen was attached to 1-inch diameter cylinders by means of an epoxy adhesive. The assembly, cylinder-specimen-cylinder, is placed in an alignment fixture for curing of the adhesive under a controlled compressive load. It is then placed in an Instron table model tensile tester between self aligning supports to determine the load required to cause rupture of the specimen.

FIBER STIFFNESS

The fiber property of special interest in this project is fiber bending or flexural stiffness. It is defined as the product of the fiber modulus of elasticity and the area moment of inertia of the fiber cross section. Nethercut (7) determined the flexural stiffness of synthetic fibers by mounting them as cantilevers, exciting them with sound waves, and noting their resonant frequency. The flexural stiffness was calculated from the measured resonant frequency. Nethercut was unable to apply this technique to wood fibers. James (8) used a slightly different technique to determine flexural stiffness. The individual fibers were straightened and one end of the fiber glued to a fixed base. A small steel ball was glued to the other end of the fiber. This assembly was placed in an airtight compartment and the air evacuated. The fiber-steel ball assembly was then excited by an electromagnet, the resonant frequency recorded; and the bending stiffness calculated from the resonant frequency. Approximately 100 fibers must be tested to obtain data that will give a meaningful average of fiber stiffness for a given pulp sample. Such a procedure is very time consuming. A test method is needed which can measure the average compressive modulus of elasticity of a large group of fibers.

Although the tensile modulus and strength of single fibers have been measured, no one has measured the axial compressive modulus of elasticity or the axial compressive ultimate strength of a single fiber.

FIBER COMPLIANCE

Wood fibers are made up of a number of distinct layers. Of these, the S_2 layer makes up the bulk of the material of the fiber (about 60%). This layer consists of orthotropic fibrils which are wound around the fiber at an inclined angle to the axis of the fiber. Thus the S_2 layer may be thought of as an orthotropic element in which the orthotropic axis is not aligned with the fiber axis. This means an axial force on the fiber will produce shear stresses within the S_2 layer if the fiber is clamped at both ends (9). Thus the modulus measured in a single fiber test depends on the fibril properties, fiber geometry, and boundary conditions. This is true for either a tensile test or a compression test.

The mechanical properties of a fiber that has been removed from a pulp slurry and dried are not the same as the mechanical properties of fibers dried *in situ* in a sheet because the latter have been dried under restraints. The paper sheet is made up of a layered network of fibers, which may be twisted and bent, and which are bonded to one another. Very few fibers remain straight. A single fiber may be bonded to as many as 100 other fibers. For a well-bonded sheet, the length of the free span between fiber bonds along the axis of the fiber is about the same dimension as the fiber width. The extent of bonding depends on the fiber flexibility (or stiffness) and the geometry of the cross section. Wood pulp fibers are originally shaped like a tube with tapered ends. Springwood fibers have thin walls and will collapse into a ribbon-like fiber, whereas summerwood fibers have thick cell walls and may retain an oval shape in the fiber mat. A typical sheet can have approximately 10-20 layers of fibers, with most fibers lying more or less flat. To separate the fibers, the sheet must be soaked apart and, by so doing, the mechanical properties of the individual fibers would again change.

In this work the fiber modulus of pulped fibers was measured before they were formed into a sheet. The wood chips were cooked and washed, but not dispersed. Small fiber bundles were cut from the chips and prepared for testing (Fig. 2). The ends of a bundle were cut perpendicular to the long axis of the fibers by using the flat surface of two large supporting cylinders as a guide (Fig. 3). The cuts were made with a specially sharpened razor blade (tapered on one side only) under a microscope. The faces parallel to the axis of the fiber were formed by cutting away rows of fibers until a column of fibers remained. This is done with a squared end of a bundle resting on a solid block. The fiber columns were essentially rectangular in cross section and contained approximately 100 to 150 fibers (Fig. 4), with a length of 1.5 mm. The columns were glued to pins having flat ends 0.8 mm in diameter (Fig. 5). This assembly of pin-fibers-pin, was placed in the IPC single fiber load elongation tester (Fig. 6) for measurement of the load-deformation relationships in compression and tension (Fig. 7). After testing, the columns were sectioned. Thin sections were placed on microscope slides, stained, and analyzed with a Bausch and Lomb image analyzer to obtain the total cross-sectional area of the fiber cell wall material in the column. The average fiber axial modulus was computed from the initial straight-line portion of the load-deformation curve, the length of the column, and the cross-sectional area of the fiber cell wall material.

The advantages of testing the fibers in this manner are:

1. The fibers are initially straight.
2. One test gives an average for the modulus of elasticity, whereas in other techniques each individual fiber is measured requiring up to 100 tests in order to determine an average value.

The area moment of inertia (I) is defined as:

$$I = \int \int y^2 \, dA$$

where y is the distance from the axis passing through the geometric center of the fiber to the differential area dA.

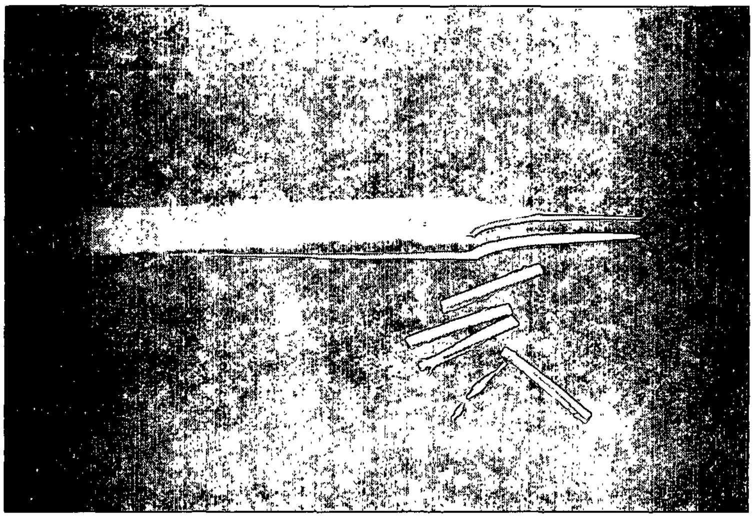

Figure 2. Fiber Bundles After Pulping and Before Testing

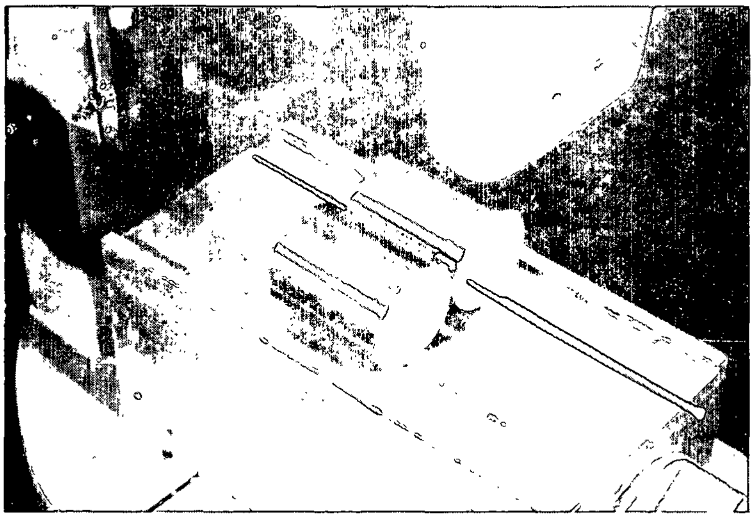

Figure 3. Fiber Bundle in Preparation for Compression Test

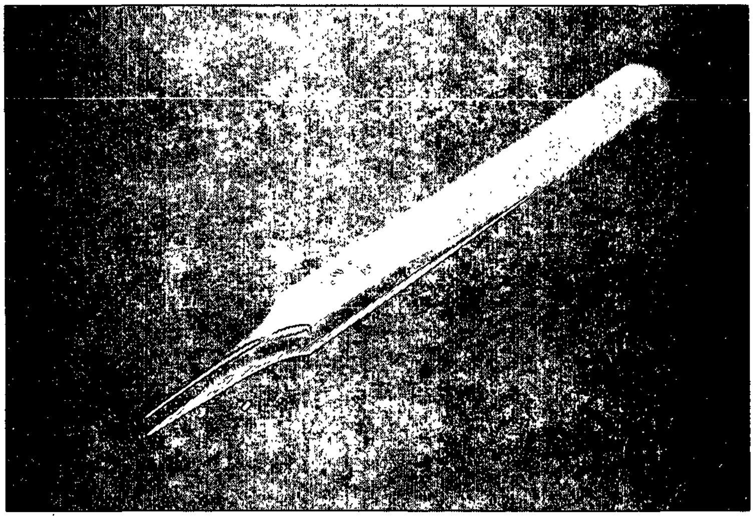

Figure 4. Fiber Column Ready to be Mounted in Test Fixture

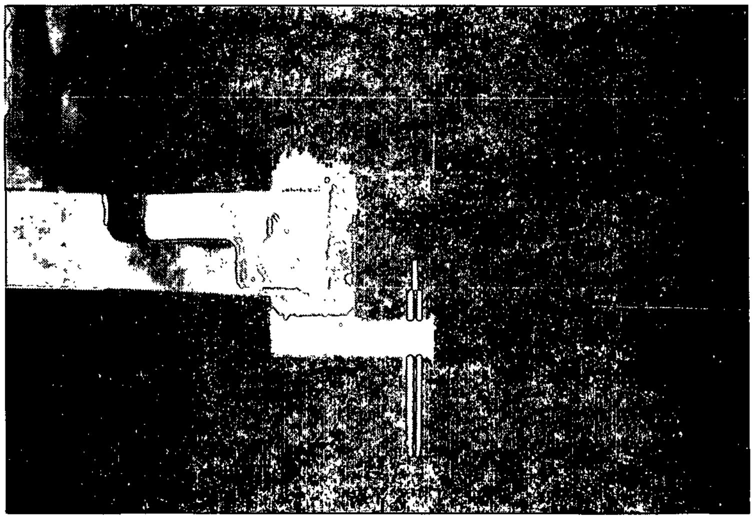

Figure 5. Fiber Column Glued to Pin

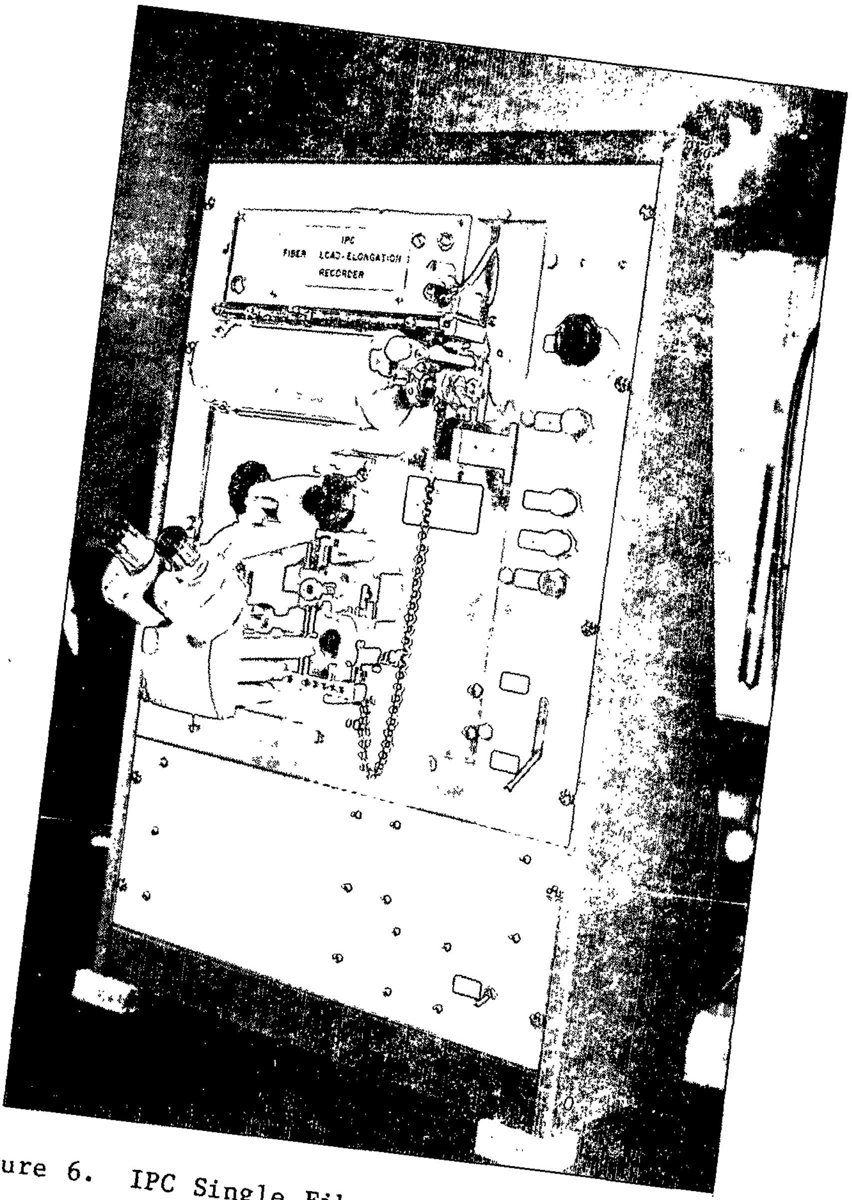

Figure 6. IPC Single Fiber Load-Elongation Tester

The value of I for individual fibers was determined by sectioning the handsheets and photographing them in a scanning electron microscope. The coordinates of the inside and outside fiber walls were determined from the SEM photograph using a digitizer. The coordinates were punched onto computer cards which were used with a computer program to determine the moment of inertia of individual fibers according to the above equation.

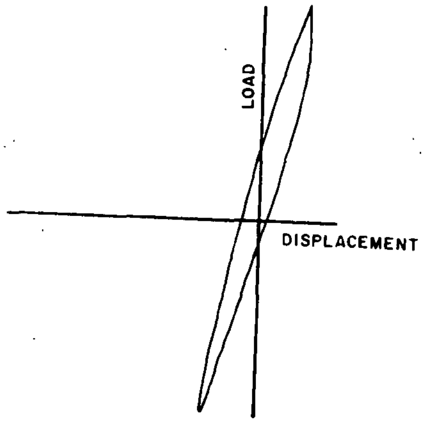

Figure 7. Relationship Between Fiber Column Displacement and Applied Load

FIBER DIMENSIONS

The four species of trees chosen for the project were Douglas-fir, loblolly pine, Virginia pine, and southern gum. These species are commonly used in linerboard production. Typical fiber lengths are given in Table I.

TABLE I

TYPICAL FIBER LENGTHS

Douglas-fir	3.9 mm[a]
Loblolly pine	3.6 mm
Virginia pine	2.1 mm
Southern gum	1.7 mm

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[a] "Pulpwoods of United States and Canada" - Irving Isenberg.

All species, except the gum, have distinct growth rings and were chipped by hand to separate the earlywood and the latewood fibers. Typical dimensions of the fibers are given in Table II.

TABLE II

TYPICAL FIBER DIMENSIONS

	Wall Thickness, µm	Radial Diameter, µm	Tangential Diameter, µm
Douglas-fir earlywood	1.48	31.5	38.9
Douglas-fir latewood	4.99	19.6	20.9
Loblolly pine earlywood	1.58	38.6	32.0
Loblolly pine latewood	4.01	21.8	23.7
Virginia pine earlywood	1.94	30.9	28.2
Virginia pine latewood	3.69	18.9	24.7
Southern gum	3.58	14.6	14.3

Each of these seven fiber divisions was separately cooked, washed, formed into handsheets, and press-dried.

HANDSHEET PREPARATION AND PROPERTIES

Each of the seven types of chips was cooked using the kraft process to produce a yield of approximately 50% (Table III). After cooking, the chips were washed and sample fiber bundles were removed for the determination of the fiber compressive modulus of elasticity.

The remaining pulp was disintegrated for 300 counts in a British disintegrator, leaving a large number of shives. These were removed by screening over a 12-mesh screen mounted onto the bottom of a 12-cut Valley flat screen. The pulp was washed in the flat screen, dewatered in a centrifuge, and stored at 40°F for several days prior to the preparation of the handsheets. Approximately 4-gram handsheets (oven dry basis) were made from the screened pulp using a British sheet mold. These were couched off the wire using three dry, new blotters. The handsheets were wet pressed and dried under pressure to a moisture equilibrium with 50% RH and 73°F. Subsequent tests were made at the same humidity and temperature conditions.

TABLE III

YIELD AND KAPPA NUMBER OF COOKED CHIPS

	% Yield	Kappa No.
Douglas-fir earlywood	48.4	62.3
Douglas-fir latewood	49.4	66.3
Loblolly pine earlywood	49.1	67.6
Loblolly pine latewood	49.91	64.5
Virginia pine earlywood	47.9	62.5
Virginia pine latewood	49.5	64.7
Southern gum	48.1	18.6

Tests were made to determine the following properties:

Basis weight
Thickness at zero load
Density
Tensile strength
Modified ring compression
STFI compression strength
Weyerhaeuser compression strength
z-Direction tensile strength
Relative bonded area

Thickness was measured with a special micrometer in which soft rubber platens contact the sheet. The soft rubber conforms to the contour of the sheet surface under low loads. Measurements of thickness *versus* applied transverse load were made in the pressure range 3.7 to 6.5 psi. Within this range, thickness measurements were made at load increments of 100 grams. The thickness corresponding to zero load was found by extrapolation of the plotted results.

The sheet density was determined from the basis weight and the zero load thickness.

PRESS-DRYING

Fiber-to-fiber bonding within the handsheets was varied by applying different levels of press drying pressures. The wet handsheets were placed between blotters which in turn were placed in a press. The load was held constant until the handsheets were dried to moisture equilibrium with 50% RH and 73°F. Typically, 15 blotters, preconditioned to moisture equilibrium with 10%, RH were placed on each side of each handsheet. Four or five press drying pressures were applied to each of the furnishes, to produce sheets of four different densities within each furnish. The pressures are given in Table IV.

TABLE IV

PRESS DRYING PRESSURE - PSI

Douglas-fir earlywood	0.226	2.9	7.5	20.0	
Douglas-fir latewood	0.226	5.0	20.0	100.0	
Loblolly pine earlywood	0.226	2.0	8.0	20.0	
Loblolly pine latewood	0.226	12.6	40.0	100.0	
Virginia pine earlywood	0.226	6.0	14.0	20.0	
Virginia pine latewood	0.226	12.6	40.0	100.0	
Gumwood	0.226	6.0	15.0	55.0	90.0

The wet pressing and drying pressure influences the density of the handsheet; increased pressure results in increased density (Fig. 8 and 9). At the lowest pressing pressure the fiber network is uncompressed and poorly bonded (Fig. 10 and 11). As the pressing pressure is increased, the network forms a more closed structure with collapsed fibers. The pressing pressure forces the fibers into closer contact with one another, resulting in a greater bonded area by increasing both the area per bond and the total number of bonds. The effect of increasing pressure is seen in the sequence of Fig. 10-13 for earlywood and 14-17 for latewood. At the highest wet pressing and drying pressure the individual fibers are collapsed and the network quite closed.

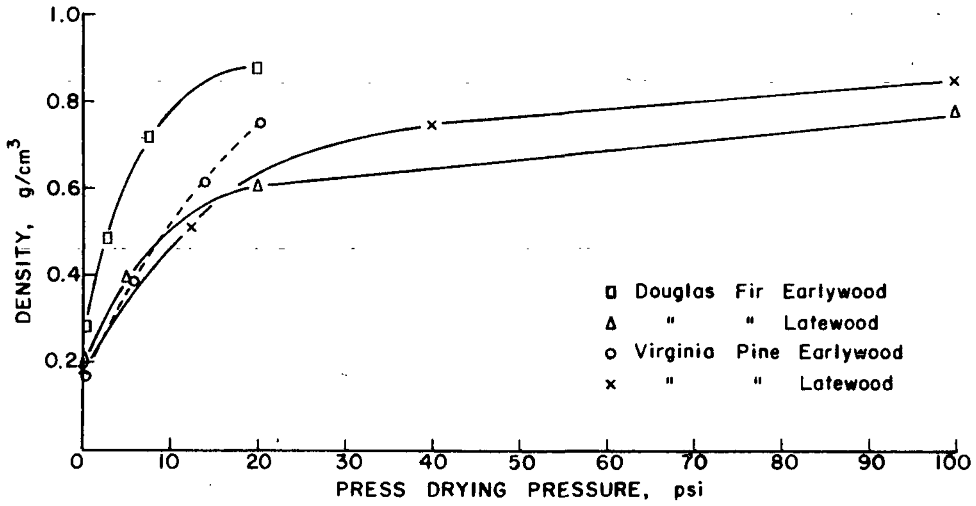


Figure 8. Relationship Between Press Drying Pressure and Sheet Density - Douglas-Fir, Virginia Pine

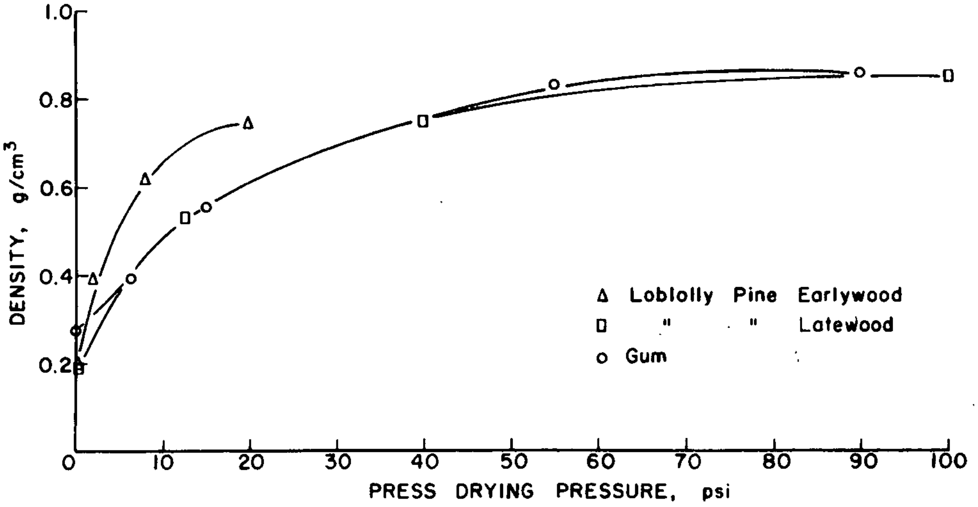


Figure 9. Relationship Between Press Drying Pressure and Sheet Density - Loblolly Pine, Gum

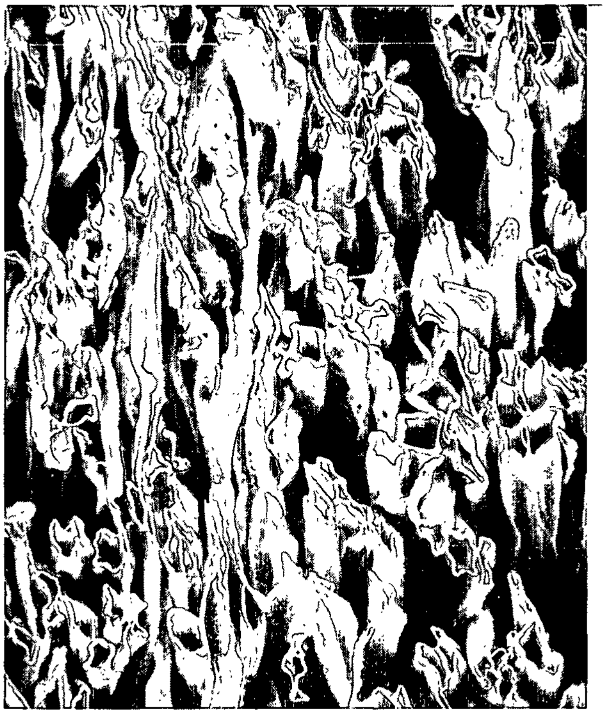


Figure 10. Virginia Pine Earlywood, Sheet Density 0.172 g/cm^3

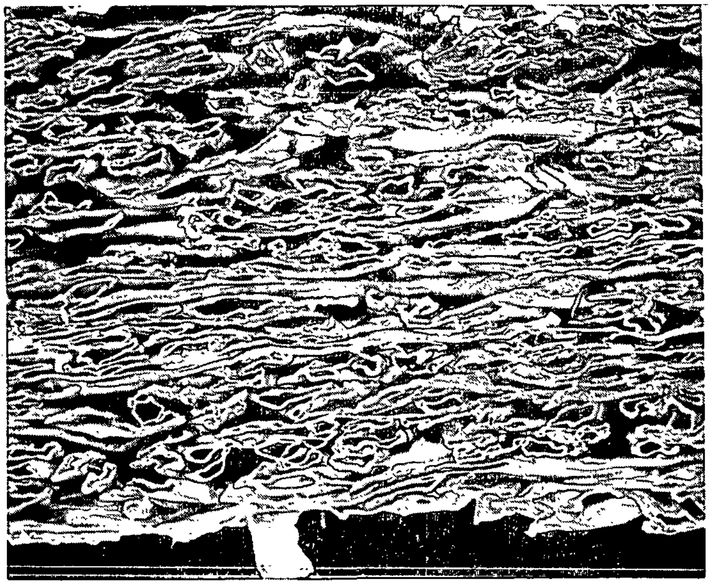


Figure 11. Virginia Pine Earlywood
Sheet Density 0.442 g/cm^3

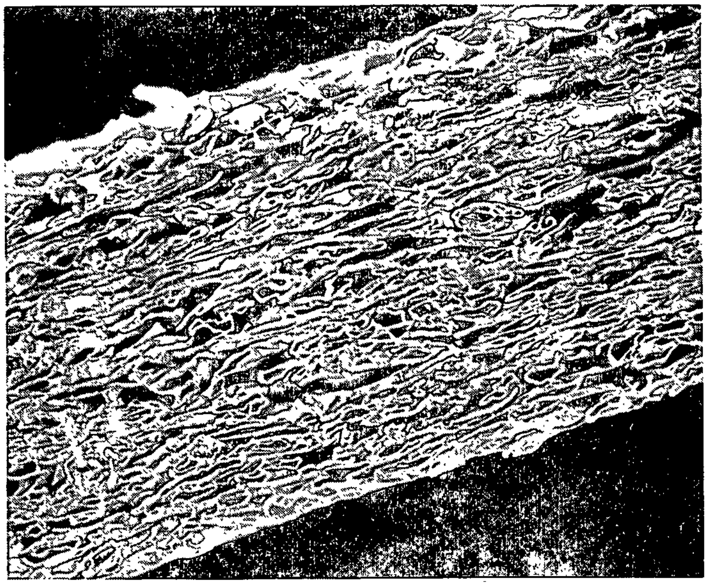


Figure 12. Virginia Pine Earlywood
Sheet Density 0.547 g/cm^3

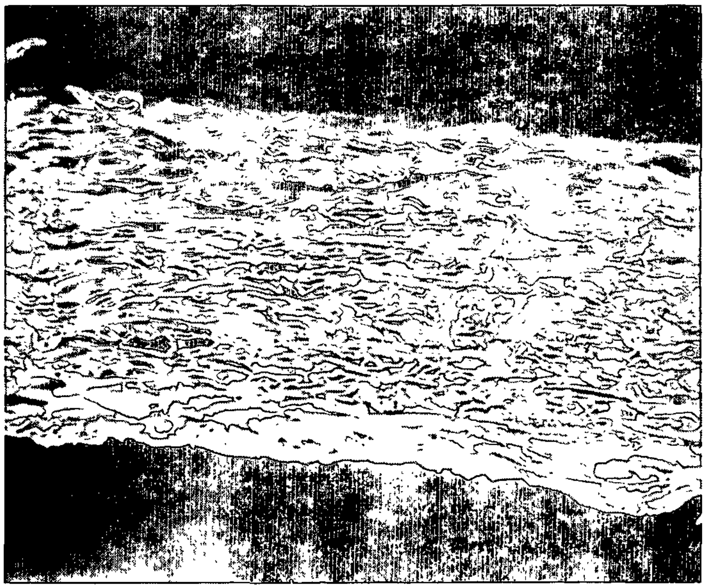


Figure 13. Virginia Pine Earlywood Sheet Density 0.769 g/cm^3

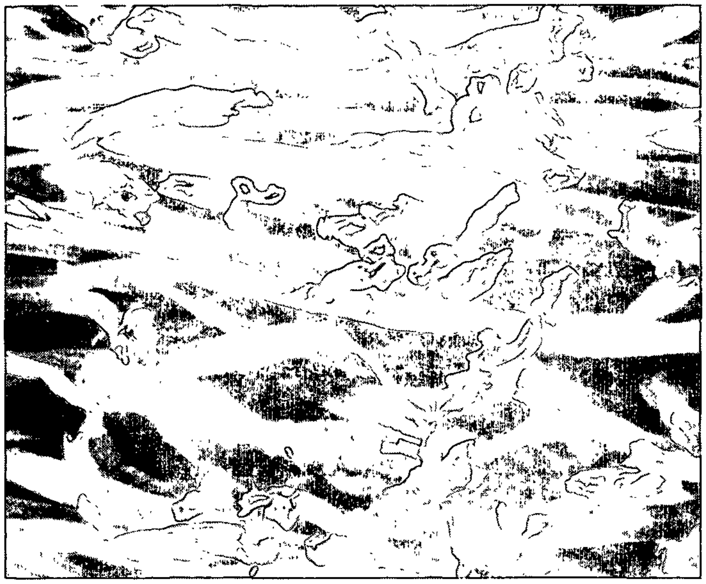


Figure 14. Virginia Pine Latewood, Sheet Density 0.182 g/cm^3

Figure 15. Virginia Pine Latewood, Sheet Density 0.505 g/cm^3

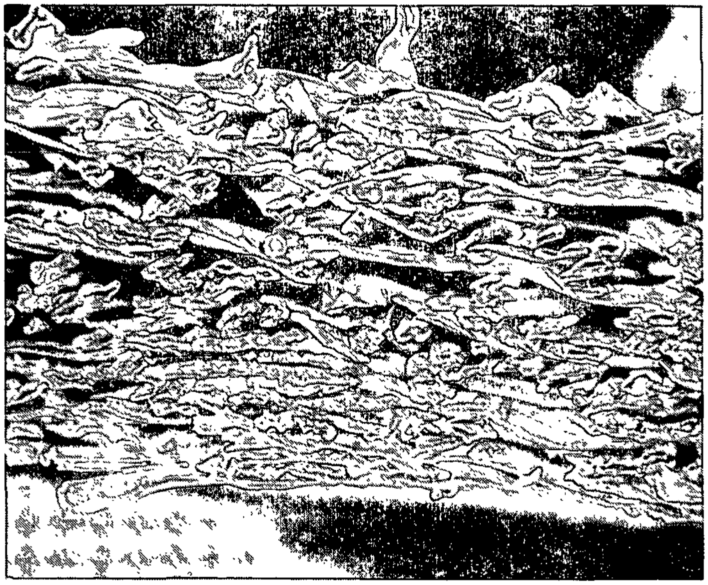


Figure 16. Virignia Pine Latewood, Sheet Density 0.755 g/cm^3

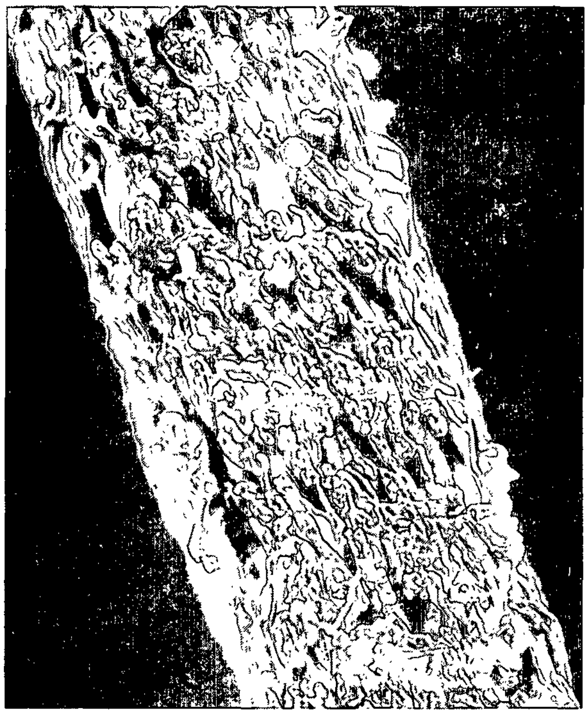


Figure 17. Virginia Pine Latewood, Sheet Density 0.845 g/cm^3

RESULTS

The objective of this project was to determine the relative importance of fiber-to-fiber bonding and fiber stiffness on the compressive strength of linerboard. The information that pertains to the role of fiber bonding can best be displayed graphically in terms of compressive strength vs. density, compressive strength vs. z-direction tensile strength, relative bonded area vs. density, compressive strength vs. RBA, tensile modulus vs. compression modulus, and the ratio of tensile strength to compressive strength vs. density.

COMPRESSIVE STRENGTH vs. SHEET DENSITY

Sheet density can be taken as an indication of the degree of bonding within the sheet. The higher the density the greater the bonded area within the fiber network. When compressive strength is plotted against handsheet density, it is very clear that density increases result in compressive strength increases (Fig. 18-21). Each figure contains the data for a single wood species. Each data point represents an average of measurements on three sheets. Figure 18 for the loblolly pine earlywood and latewood shows a steady increase in compressive strength with density. The exception is the last data point for the latewood sheet at a density of 0.84 g/cm^3, where the compressive strength is slightly below that of the earlywood sheet at a density of 0.76 g/cm^3. It is interesting to note that all the data lie close to a single line except the first and last latewood densities. A plot of compressive strength vs. sheet density for the Douglas-fir (Fig. 19) is similar to that for the loblolly pine. In fact, the compressive strengths of these two materials at a given density are nearly identical.

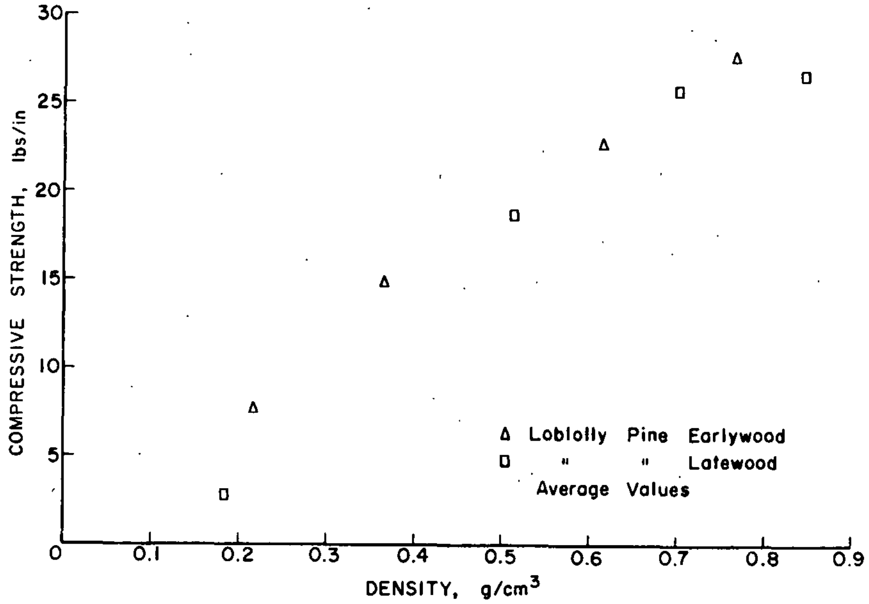


Figure 18. Relationship Between Compressive Strength and Density - Loblolly Pine

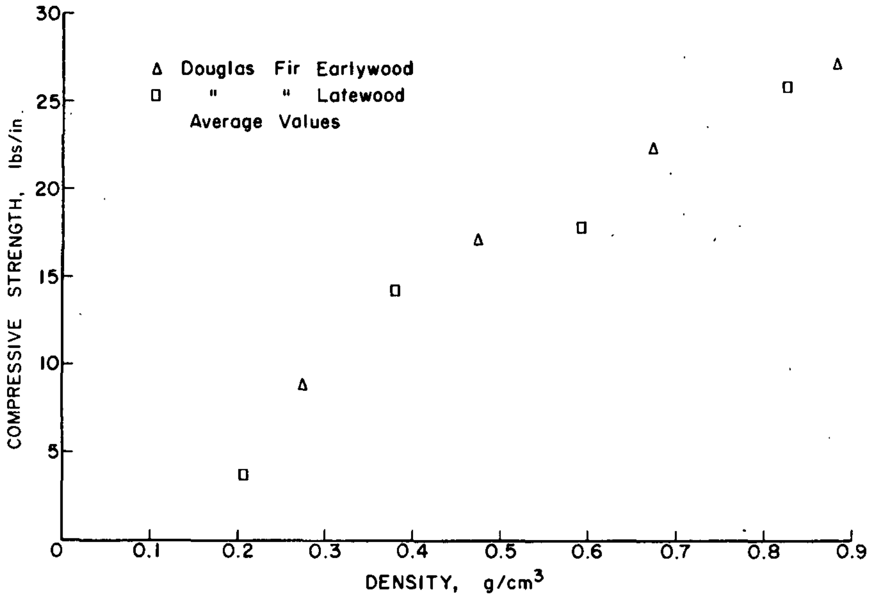


Figure 19. Relationship Between Compressive Strength and Density - Douglas-Fir

The Virginia pine data show a clear distinction between earlywood and latewood (Fig. 20). The southern gum, the species with the shortest fibers, the highest fiber modulus, and the lowest bending stiffness, has the highest value of compressive strength (Fig. 21). All of the data show that compressive strength is a strong function of sheet density.

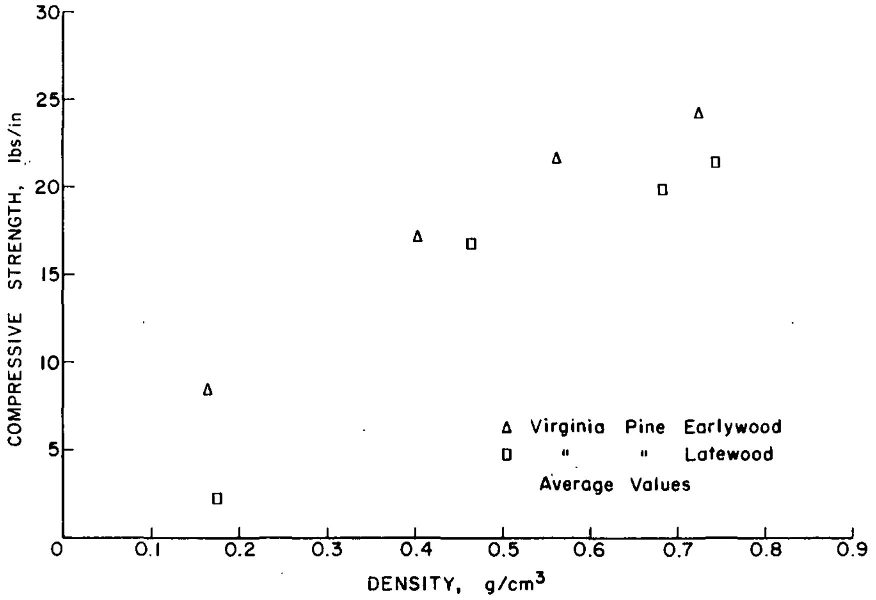


Figure 20. Relationship Between Compressive Strength and Density - Virginia Pine

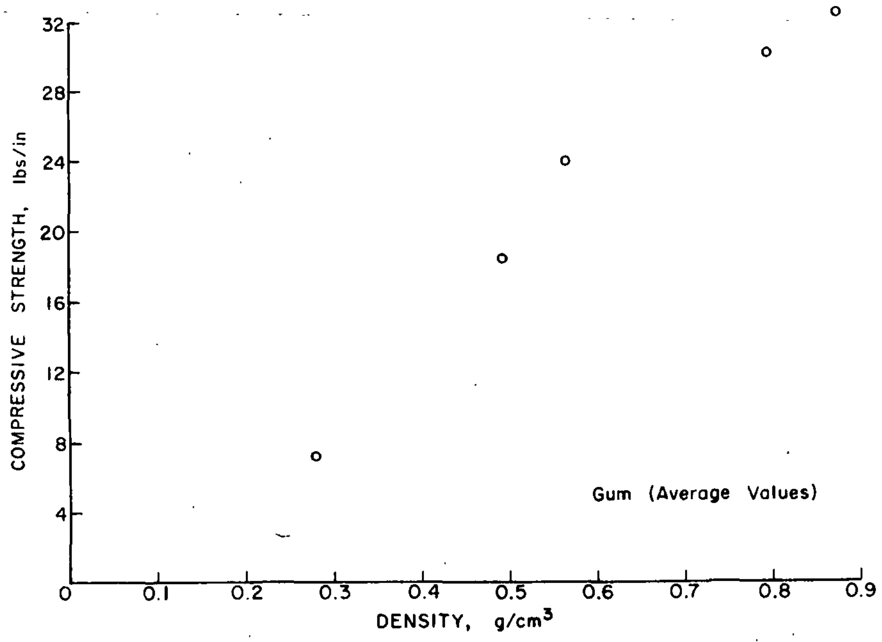


Figure 21. Relationship Between Compressive Strength and Density - Gum

COMPRESSIVE STRENGTH vs. z-DIRECTION TENSILE STRENGTH

The compressive strength can also be plotted against the z-direction tensile strength of the sheets. The z-direction tensile strength can be considered a measure of the strength of the bonds within the sheet. The results demonstrate that as z-direction tensile strength increases, so does compressive strength (Fig. 22-25). The increase in compressive strength, however, is greatest at low z-direction tensile strength values. The compressive strength curve "flattens out" at higher values of z-direction tensile. This may indicate that the bond strength is no longer critical with regard to compressive strength, or it may indicate insensitivity in measuring true bond strength with the z-direction tensile test procedure.

It is interesting to note that for the Douglas-fir and loblolly pine handsheets, the compressive strength values are almost identical for the same value of z-direction tensile strength (Fig. 22,23). The Virginia pine develops less compressive strength than the other pulps, especially at higher levels of z-direction tensile strength (Fig. 24). The gum developed the highest levels of z-direction tensile strength and the highest of compression strength (Fig. 25).

The initial portion of these curves (Fig. 22-25) and the curves for compressive strength vs. density (Fig. 18-21) are similar. Compressive strength increases rapidly with bonding (density). The curves differ at higher values of the independent variable, however, in that compressive strength versus z-direction tensile strength reaches a plateau, whereas it does not when plotted against density.

As discussed earlier, the relative bonded area (RBA) of the handsheets was measured using the gas absorption technique. RBA and density are related as shown in Fig. 26-27. A straight line relationship exists for the Douglas-fir pulp. It is evident that plots of compression strength vs. RBA (Fig. 28-31) would be similar to plots of compressive strength vs. sheet density. Such plots show that the total bond area is important as well as the strength of the bonds. The significance of this fact will be evident when the results of compressive strength vs. fiber stiffness are discussed.

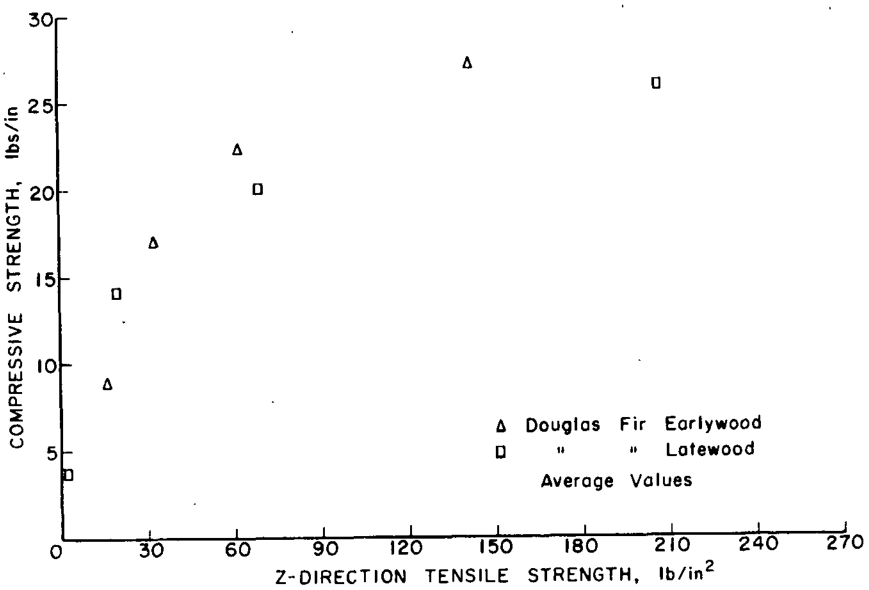


Figure 22. Relationship Between Compressive Strength and z-Direction Tensile Strength - Douglas-Fir

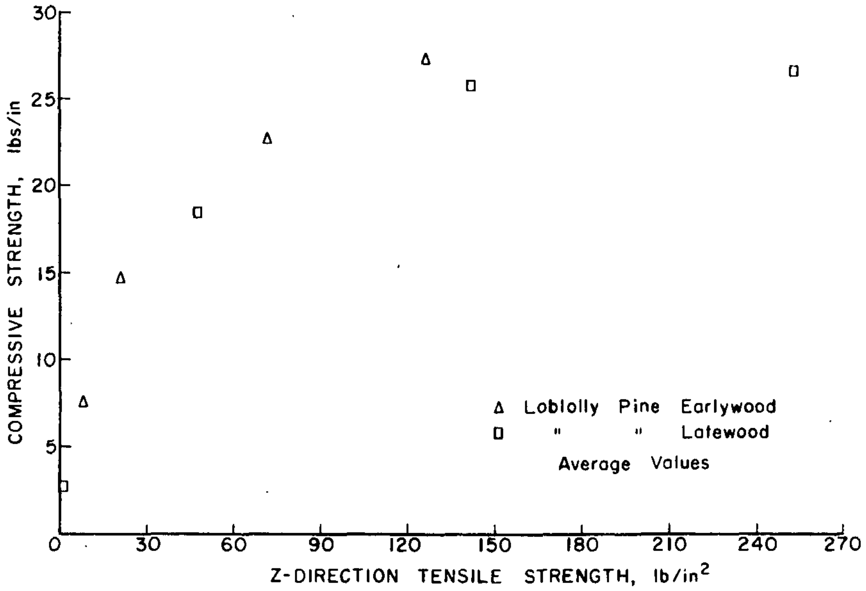


Figure 23. Relationship Between Compressive Strength and z-Direction Tensile Strength - Loblolly Pine

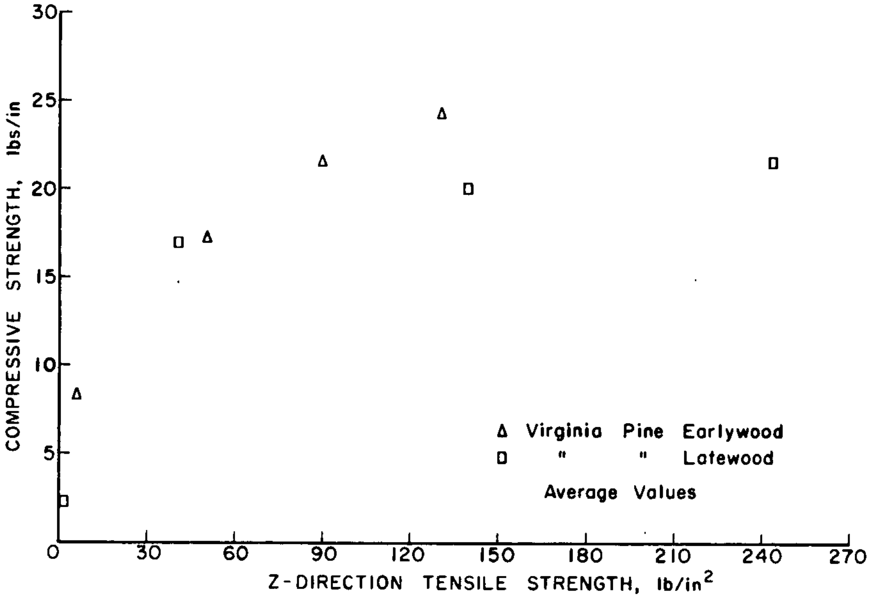


Figure 24. Relationship Between Compressive Strength and z-Direction Tensile Strength - Virginia Pine

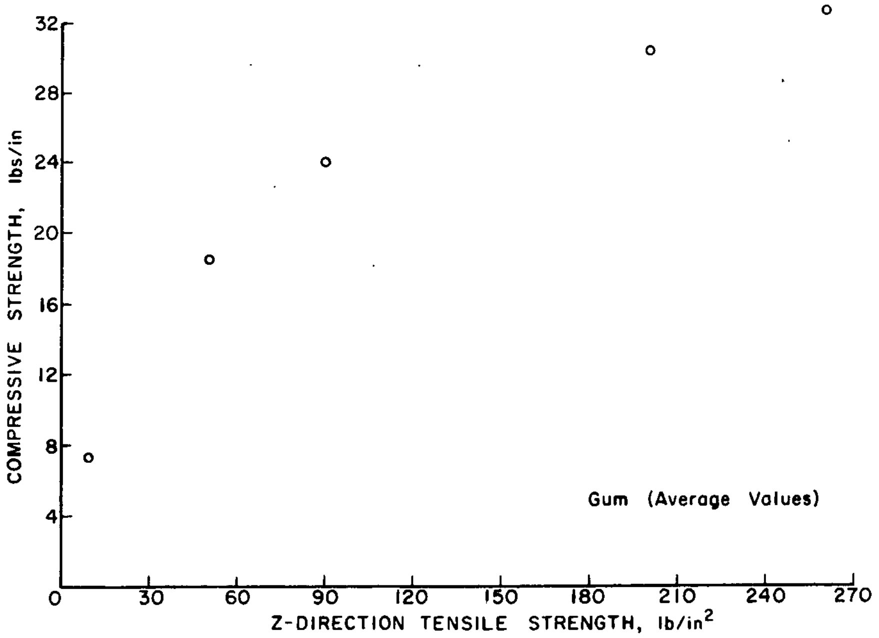


Figure 25. Relationship Between Compressive Strength and z-Direction Tensile Strength - Gum

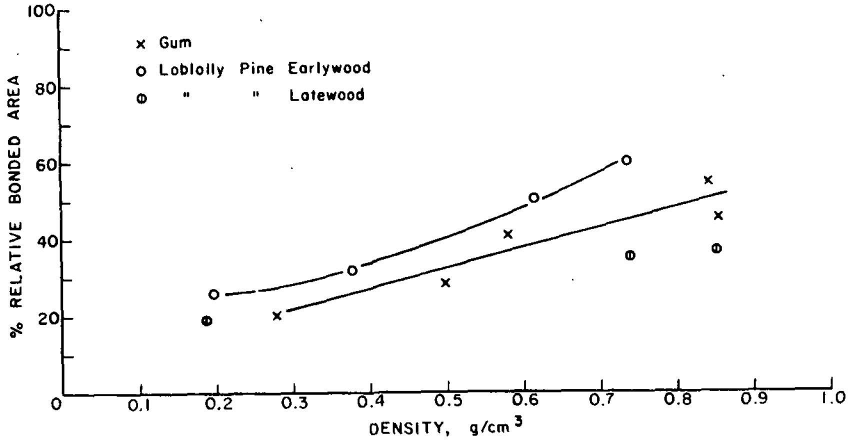


Figure 26. Relationship Between Relative Bonded Area and Density - Loblolly Pine, Gum

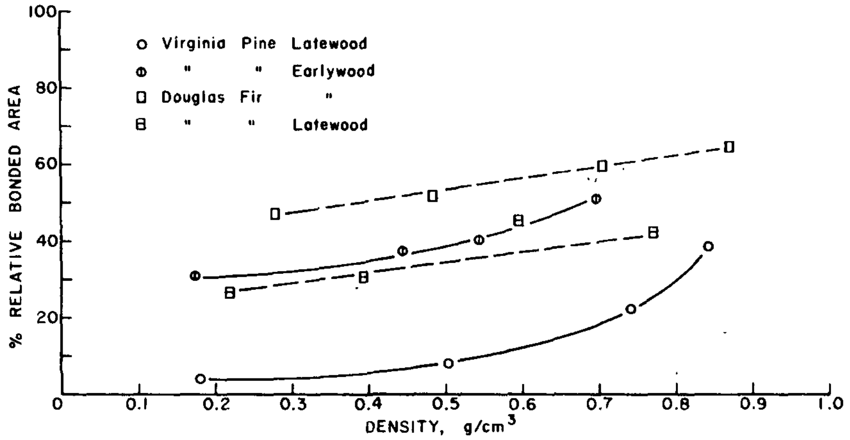


Figure 27. Relationship Between Relative Bonded Area and Density - Virginia Pine, Douglas-Fir

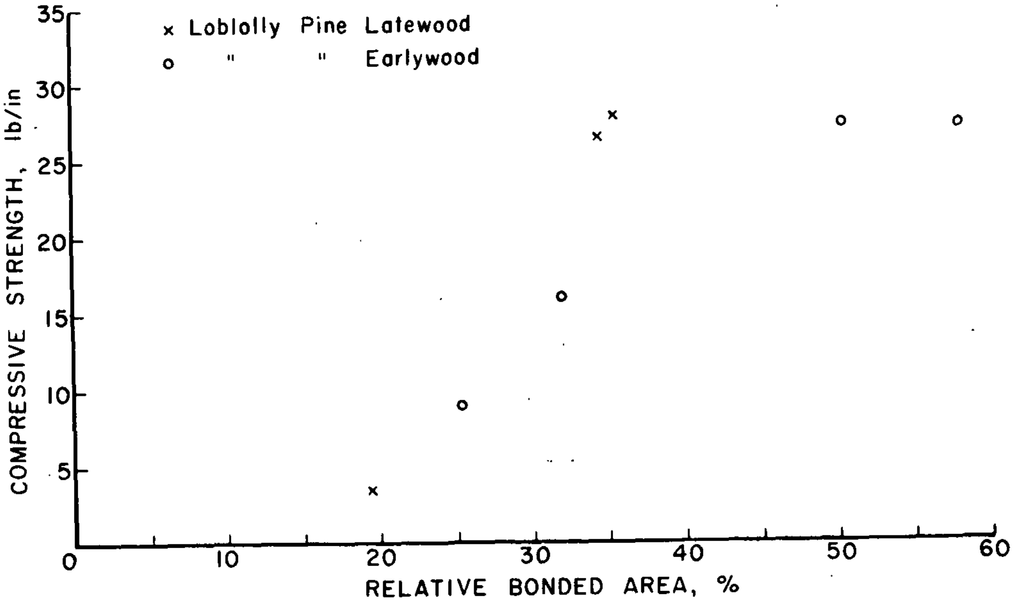


Figure 28. Relationship Between Compressive Strength and Relative Bonded Area - Loblolly Pine

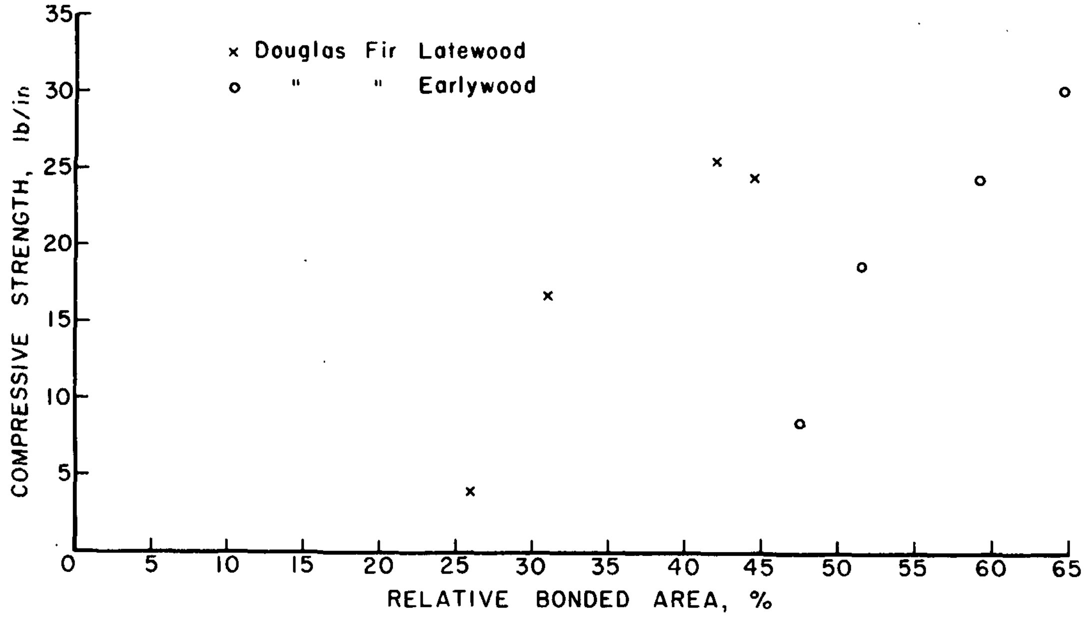


Figure 29. Relationship Between Compressive Strength and Relative Bonded Area - Douglas-Fir

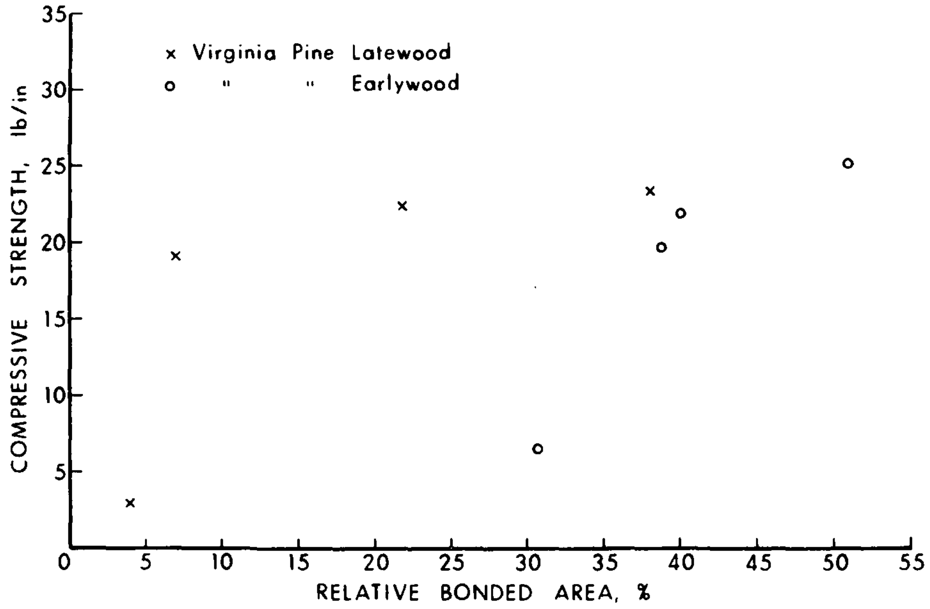


Figure 30. Relationship Between Compressive Strength and Relative Bonded Area - Virginia Pine

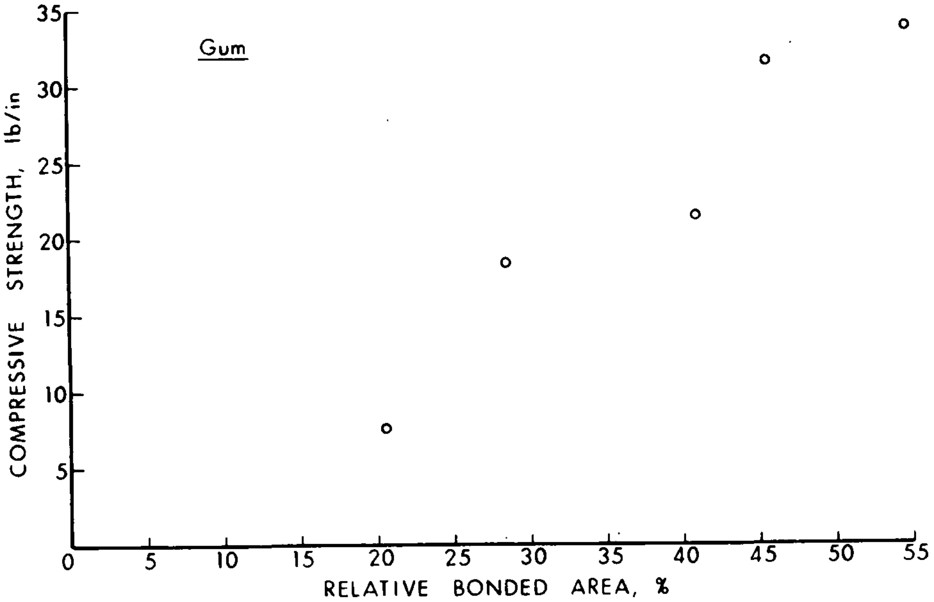


Figure 31. Relationship Between Compressive Strength and Relative Bonded Area - Gum

COMPRESSIVE PROPERTIES *vs*. TENSION PROPERTIES

There are two other relationships which can be investigated for these sheets, that between compressive and tensile modulus, and the ratio of tensile strength to compressive strength as a function of density. The tensile and compressive moduli were determined on different specimens taken from the same sample. It would be expected that the two moduli would be the same and this is the case (Fig. 32).

Figures 33-35 show the ratio of tensile strength/compressive strength *vs*. sheet density. No trend is evident; the ratio varies between 2 and 3.5.

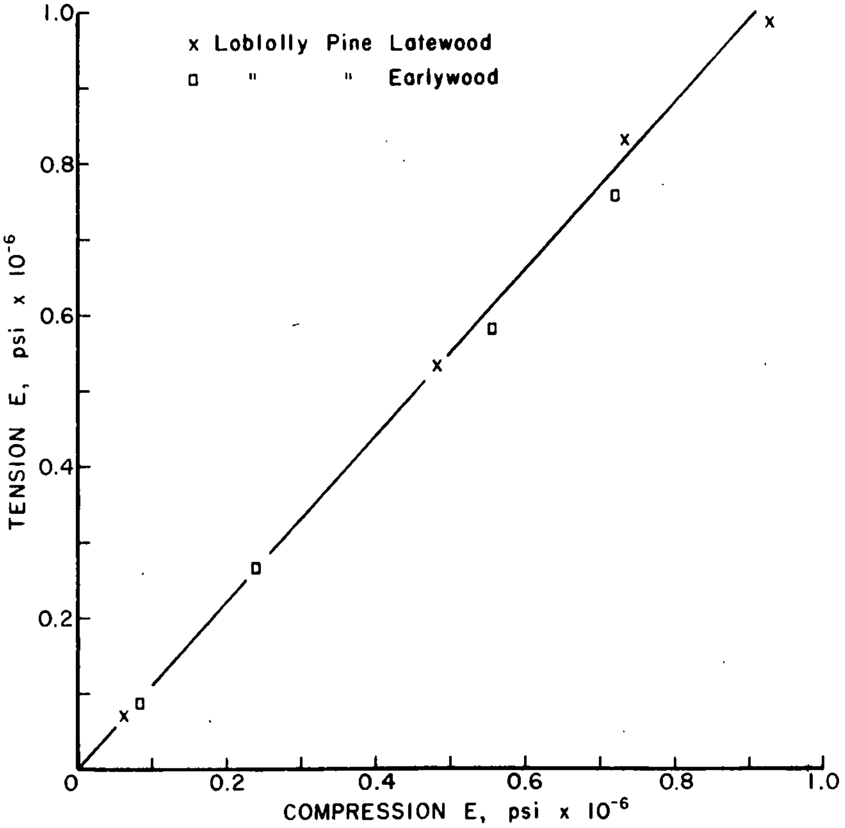


Figure 32. Typical Comparison Between Sheet Tensile Moduli and Compression Moduli

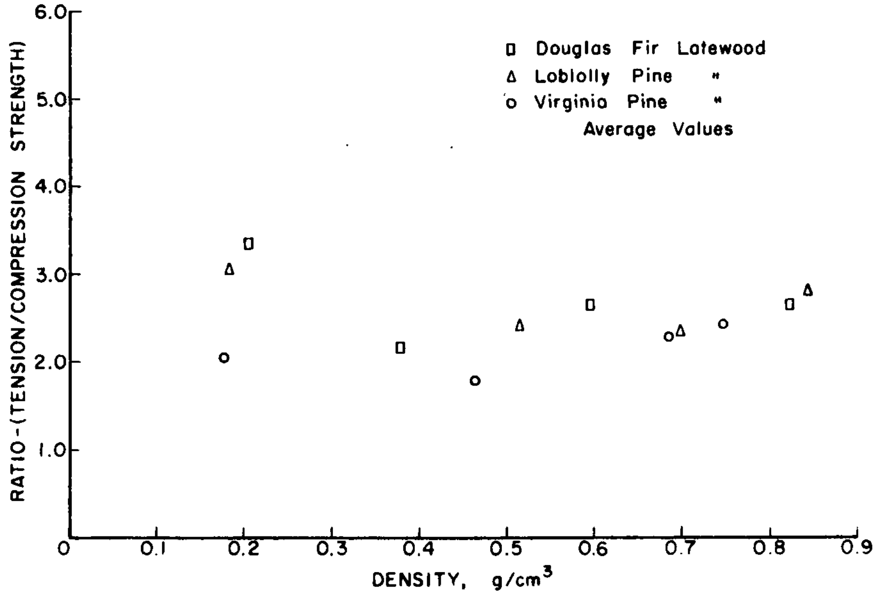


Figure 33. The Relationship Between the Ratio of (Tensile/ Compressive) Strength and Sheet Density - Latewood

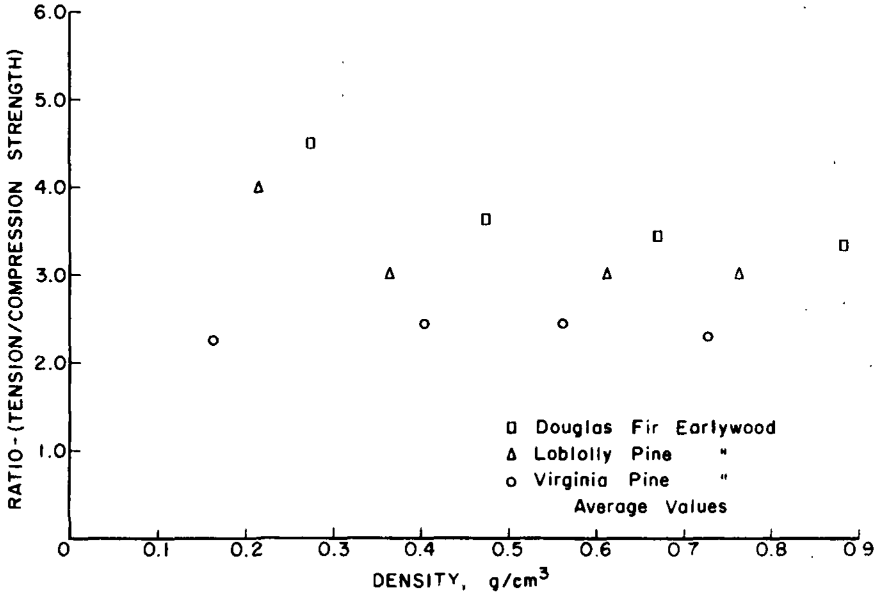


Figure 34. The Relationship Between the Ratio of (Tensile/Compressive) Strength and Sheet Density - Earlywood

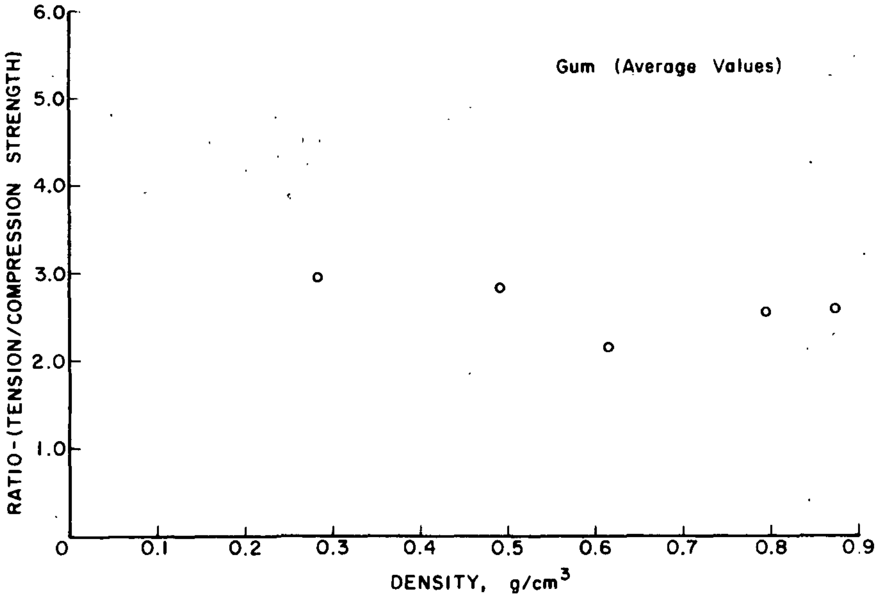


Figure 35. The Relationship Between the Ratio of (Tensile/Compressive) Strength and Sheet Density - Southern Gum

COMPRESSIVE PROPERTIES AND FIBER MODULUS

The fiber compressive modulus was measured as discussed earlier, and the results are given in Table V. The earlywood and latewood fibers of a given species have similar moduli. Among the species the Virginia pine has the lowest modulus, followed by Douglas-fir, loblolly pine, and southern gum with the highest modulus.

TABLE V

COMPRESSIVE MODULUS OF FIBERS

Virginia pine earlywood	-	0.74×10^6 psi
Virginia pine latewood	-	0.73×10^6 psi
Douglas-fir earlywood	-	0.95×10^6 psi
Douglas-fir latewood	-	0.85×10^6 psi
Loblolly pine earlywood	-	1.0×10^6 psi
Loblolly pine latewood	-	0.92×10^6 psi
Southern gum	-	1.1×10^6 psi

The sheet compressive modulus correlates very well with the compressive modulus of the fiber (Table VI). The sheet compressive modulus values are those for the sheet formed at the highest pressing and drying pressure. The general trend is, the higher the fiber modulus, the higher the sheet modulus.

The fiber compressive modulus can also be compared to the ultimate compression strength of the sheet (Table VII). The correlation between the two is quite good. A detailed discussion of this point will follow the presentation of fiber stiffness.

TABLE VI

RANK OF FIBER MODULUS AND SHEET MODULUS

	Compressive Fiber Modulus, psi	Rank	Compressive Sheet Modulus, psi	Rank
Virginia pine earlywood	0.74×10^6	2	0.46×10^6	2
Virginia pine latewood	0.73×10^6	1	0.45×10^6	1
Douglas-fir earlywood	0.95×10^6	5	0.81×10^6	4
Douglas-fir latewood	0.85×10^6	3	0.86×10^6	6
Loblolly pine earlywood	1.0×10^6	6	0.69×10^6	3
Loblolly pine latewood	0.92×10^6	4	0.83×10^6	5
Southern gum	1.1×10^6	7	0.91×10^6	7

TABLE VII

RANK OF FIBER MODULUS AND SHEET COMPRESSIVE STRENGTH

	Compressive Fiber Modulus, psi	Rank	Sheet Compression Strength, lb/inch	Rank
Virginia pine earlywood	0.74×10^6	2	24.3	2
Virginia pine latewood	0.73×10^6	1	21.5	1
Douglas-fir earlywood	0.95×10^6	5	27.1	5
Douglas-fir latewood	0.85×10^6	3	26.0	3
Loblolly pine earlywood	1.0×10^6	6	27.4	6
Loblolly pine latewood	0.92×10^6	4	26.7	4
Southern gum	1.1×10^6	7	32.5	7

Since the fiber and sheet moduli are related, and the former is related to the sheet compressive strength, one would also expect the sheet modulus to be related to the sheet compressive strength. This is the case as shown in Table VIII. In general, the higher the sheet modulus, the higher the ultimate compressive strength. These results suggest that if an on-line measurement of initial sheet modulus could be made, it could be used to indirectly monitor compressive strength.

TABLE VIII

RANK OF SHEET MODULUS AND SHEET COMPRESSIVE STRENGTH

	Sheet Compressive Modulus, psi	Rank	Sheet Compressive Strength, lb/inch	Rank
Virginia pine earlywood	0.45×10^6	2	24.3	2
Virginia pine latewood	0.45×10^6	1	21.5	1
Douglas-fir earlywood	0.81×10^6	4	27.1	5
Douglas-fir latewood	0.86×10^6	5	26.0	3
Loblolly pine earlywood	0.69×10^6	3	27.4	6
Loblolly pine latewood	0.83×10^6	5	26.7	4
Southern gum	0.91×10^6	7	32.5	7

COMPRESSION PROPERTIES AND FIBER STIFFNESS

The earlywood and latewood fibers of a given species have different geometric properties. The earlywood fibers have a smaller wall thickness and greater diameter than the latewood fibers. For the fibers studied (Table IX), the cross-sectional area of an earlywood fiber is approximately half the area of the latewood fiber. However, the earlywood fiber has its mass distributed farther away from the center of the fiber than does the latewood fiber resulting in a higher area moment of inertia for the cross section. The cross-sectional area of the fibers can be calculated by using the average radius, rav, and wall thickness, t:

TABLE IX

FIBER PHYSICAL PROPERTIES

	Fiber Dimensions					
	Diameter Radial, μm	Diameter Tangential, μm	Wall Thickness, μm	Area, $(\mu m)^2$	Uncollapsed "Moment of Inertia," $(\mu m)^4$	Collapsed "Moment of Inertia," $(\mu m)^4$
Douglas-fir earlywood	31.5	38.6	1.48	156	22,000	114
Douglas-fir latewood	19.6	20.9	4.99	239	7,710	1,985
Loblolly pine earlywood	38.6	32.0	1.58	167	23,800	139
Loblolly pine latewood	21.8	23.7	4.01	236	10,800	1,265
Virginia pine earlywood	30.9	28.2	1.94	168	16,100	211
Virginia pine latewood	18.9	24.7	3.69	210	8,964	953
Southern gum	14.6	14.3	3.58	122	2,000	522

$$A = \pi t\ (2R_{av} - t)$$

and the area moment of inertia for the uncollapsed state, I uncollapsed, can be calculated from:

$$I_{\upsilon} = \frac{\pi}{4}\left[R_{av}{}^{4} - (R_{av} - t)^{4}\right]$$

The area moment of inertia for the collapsed state can be calculated from:

$$I_{c} = \frac{\pi t^{3}}{3}\ (2R_{av} - t)$$

The moments of inertia for the uncollapsed fibers are greater than those of the latewood fibers by a factor of 4 to 200 (Table IX). The reverse is true for the collapsed state, the latewood fibers have a higher moment than the earlywood fibers.

To assist in understanding what happens to a single fiber within the fiber network, let's consider what happens to a structural beam and column. A compressive load acting on a perfectly straight, thin column can buckle the column. This is the so-called Euler buckling load (Fig. 36). It is an instability phenomenon which occurs because the increase in compressive load can be absorbed with less energy by bending the column than by direct compression of the column. The critical load can be calculated from the formula:

$$P_{cr} = \pi^{2}\ \frac{EI}{\ell^{2}}\ ,$$

where E is the modulus of elasticity, I is the moment of inertia of the cross section of the column, and ℓ is the unsupported length of the column. Since the length of the column is squared in the formula, the buckling load is very sensitive to the length.

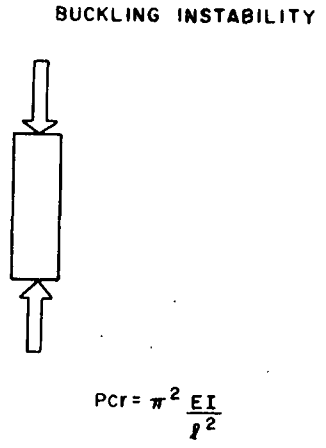


Figure 36. Buckling Instability of a Slender Column

When a column buckles, it bends much like a beam, and it is important to understand how a beam resists the loads applied to it. As the beam bends it produces compressive stresses on one side and tensile stresses on the other side. The amount that the beam bends is proportional to the length squared divided by the product of the moment of inertia and the modulus of elasticity (Fig. 37) according to:

$$e = \frac{M\ell^2}{8EI},$$

where M is the applied moment. The same physical attributes that are important in the buckling problem are important in the bending problem. Within the fiber network, fibers do not act as pure columns or pure beams; their behavior is a combination of the beam and the column.

If the column is already bent, a situation exists that is different than that discussed above. The application of the compressive load produces a moment because the application of load is not along the geometric center of the column (Fig. 38). This moment causes the beam to bend further, producing an even greater misalignment of the compressive load. Such a loading situation is called a beam column. The only thing that keeps the beam column from collapsing is its stiffness as a beam. The stresses within the beam column depend on the ratio of ℓ^2/EI. The fibers within a network would be more accurately described in terms of a beam column rather than a column.

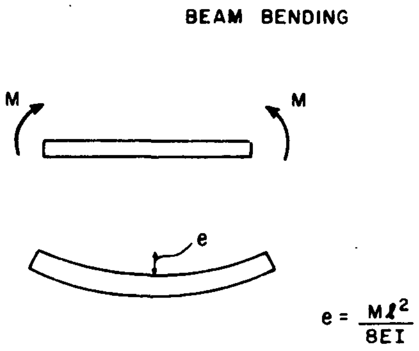
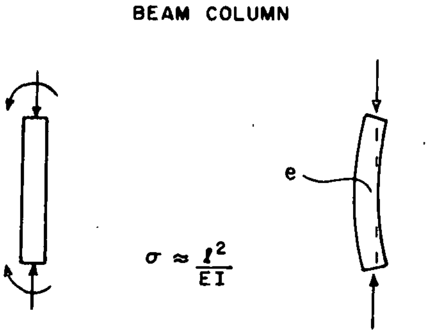


Figure 37. Bending of a Beam



initial moment leads to deflection e
which leads to more moment
which leads to more deflection

Figure 38. A Beam Column

The value of I decreases significantly in going from the uncollapsed to the collapsed fiber state (Table IX). The extent of fiber bonding is directly related to fiber collapse. Increased bonding results in more bond sites with less unsupported length between bonds. The ratio EI/ℓ^2 is the effective stiffness. As I decreases due to fiber collapse, ℓ^2 also decreases. As $\ell^2 \rightarrow 0$, the ratio $EI/\ell^2 \rightarrow \infty$, and the fibers no longer act individually, but act together as a coherent mass. The graphs of compression strength vs. density (Fig. 18-21) demonstrate this. The differences in fiber stiffnesses between springwood and summerwood lose significance as the sheet density increases.

In a poorly bonded sheet the bonds are far apart. Page and Seth (10) expressed the distance, (d), between the center of fiber bonds in terms of RBA and the fiber width (w).

$$\mathrm{RBA} = w^2/2wd$$

The unsupported fiber segment would then have the length

$$(d-w) = w\left(\frac{1}{\mathrm{RBA}} - 1\right)$$

A sheet that had an RBA of 20% would have an unsupported length of about 98 μm, if the collapsed fiber width was 65 μm. A sheet that had an RBA of 35% would have a typical unsupported length of 28 μm. This increase in RBA would increase the effective stiffness by a factor of 12. If bonding increases so that the RBA is 50%, the fiber is bonded either on the top or bottom over its entire length. In this case, the effective stiffness becomes infinite because the unsupported length goes to zero. The physical implication of this is that the fibers no longer act as individual beams and columns. The network of fibers is so dense that it behaves like a continuous mass of material. Hence individual fiber stiffness has no meaning.

Based on the above, the effect of fiber stiffness on compressive strength would be expected to be important only on poorly bonded sheets. The values calculated for the moment I (Table X) are approximate, but they do rank the fibers in order of stiffness. The bending of the fibers is a function of the modulus of elasticity and the moment which is given in Table X.

TABLE X

FIBER BENDING STIFFNESS - EI

	EI (Uncollapsed) dynes-cm^2	EI (Collapsed) dynes-cm^2
Douglas-fir earlywood	0.144	7.46×10^{-4}
Douglas-fir latewood	0.045	115.8×10^{-4}
Loblolly pine earlywood	0.164	9.6×10^{-4}
Loblolly pine latewood	0.069	80.8×10^{-4}
Virginia pine earlywood	0.082	10.7×10^{-4}
Virginia pine latewood	0.045	47.8×10^{-4}
Southern gum	0.015	39.2×10^{-4}

The fibers within the handsheets that are closest to the uncollapsed state are those formed with the lowest sheet density and have the lowest RBA. Cross sections of the Virginia pine at the lowest density levels are shown in Fig. 10 and 11. The relationship between compressive strength and density for the low density handsheets is shown in Fig. 39.

The three earlywood handsheets have a higher compressive strength than the three latewood handsheets. The uncollapsed stiffness of the earlywood fibers is greater than the latewood fibers, suggesting that fiber stiffness is important at low bonding levels. However, the z-direction tensile strength of the earlywood sheets is much higher than that of the latewood sheets. Table XI shows the effect of fiber stiffness on compressive strength, comparing Virginia pine latewood with loblolly pine latewood.

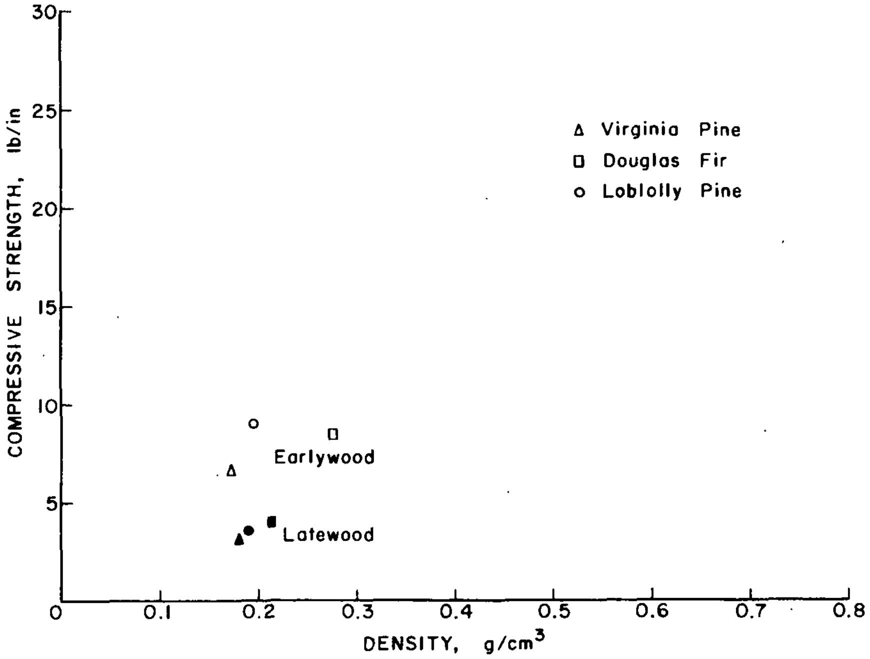


Figure 39. Relationship Between the Compressive Strength and Sheet Density for Low Levels of Bonding

TABLE XI

COMPARISON OF VIRGINIA AND LOBLOLLY PINE LATEWOODS

	z-Direction Tensile, lb/inch^2	RBA	Compressive Strength, lb/inch
Virginia pine latewood	0.71	4%	2.9
Loblolly pine latewood	0.78	20%	2.41

The bonding levels for the two fiber types, as measured by the z-direction tensile test are approximately equal and the fiber stiffnesses are of the same order of magnitude (Table X). However, due to the difference in relative bonded area, the effective stiffness is an order of magnitude higher in the loblolly pine handsheet than in the Virginia pine handsheet. Since the compressive strengths are approximately equal, the loblolly pine being only slightly higher than the Virginia pine, it seems reasonable to conclude that even at low bonding levels the influence of fiber stiffness on compressive strength is small.

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THE INSTITUTE OF PAPER CHEMISTRY

Jerald Watt

*Jerald A. Watt
Research Associate
Paper Physics Section

G.A. Baum

Gary A. Baum
Section Leader
Paper Physics Section

Clyde H. Sprague

Clyde H. Sprague
Director
Paper Materials & Systems Division

---

* Jerald A. Watt is now with the University of Wisconsin Fox Valley.