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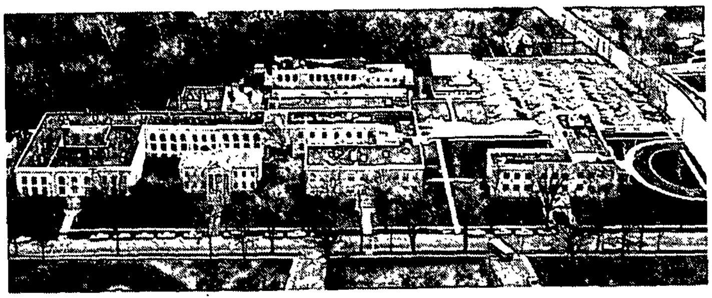

THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

STATUS REPORT

To The

PAC- PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

"This information represents a review of on-going research for use by the Project Advisory Committees. The information is not intended to be a definitive progress report on any of the projects and should not be cited or referenced in any paper or correspondence external to your company."

Your advice and suggestions on any of the projects will be most welcome.

March 22-23, 1984
The Institute of Paper Chemistry
Continuing Education Center
Appleton, Wisconsin

INSTITUTE OF PAPER CHEMISTRY
Appleton, Wisconsin

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February 29, 1984

TO: THE PROJECT ADVISORY COMMITTEE (PAC)

Enclosed is advance reading material for the March 22-23 meeting of the PAC Paper Properties and Uses Research Committee. Included are status reports for active projects, a current committee membership list, and a tentative agenda.

Rooms have been reserved in the Continuing Education Center, and meals will be provided. If you haven't already indicated your attendance, please do so at your earliest convenience by calling Sheila Burton at (414)738-3259. The combination to the front door of the Continuing Education Center will be sent later.

We look forward to seeing you on March 22-23.

Sincerely yours,

Gary Baum/sb

Gary A. Baum
Director
Paper Materials Division

GAB/sb
Enclosure

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TENTATIVE AGENDA

PAPER PROPERTIES AND USES
PROJECT ADVISORY COMMITTEE

March 22-23, 1984
The Institute of Paper Chemistry
Continuing Education Center
Appleton, Wisconsin

Thursday -- March 22

12:00 pm	-- Lunch (CEC Dining Room)	
1:00	-- Welcome/Introductions	Luce/Baum
1:15	-- Research Overview	Baum
1:35	-- PROJECT REVIEWS:	
	- Process, Properties, Product Relationships	Habeger/Baum
	- On-line Measurement of Paper Mechanical Properties	Baum/Habeger
3:00	-- Coffee Break	
	- Mechanical Testing in Shear	Waterhouse
4:00	-- SPECIAL REVIEW:	
	- Pressing and Drying	Ahrens
4:30	-- PROJECT REVIEWS:	
	- Measurement of Fiber Properties and Fiber-to-Fiber Bonding	Hardacker
	- Fundamentals of Internal Strength Enhancement	Stratton/Becher
5:30	-- Social Time	
6:00	-- Dinner (CEC Dining Room)	
7:00	-- PROJECT REVIEWS:	
	- Mechanics of Fluting	Whitsitt
	- Compressive Strength	Whitsitt/Waterhouse
	- Analysis of Board Structures	Whitsitt/Halcomb

9:00 pm -- End of Formal Session

Friday -- March 23

7:00 am -- Breakfast

8:00 -- Committee Members' Discussion of Projects

10:00 -- Coffee Break

10:20 -- Discussion of Projects and Overview

11:30 -- Closing Comments

-- Next meeting October 25-26, 1984

12:00 -- Adjourn

12:00 -- Lunch (CEC Dining Room)

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PROJECT ADVISORY COMMITTEE

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/smb
2/10/84
*date of retirement

Date: 2/13/83	
Budget: $105,000	
Period Ends: 6/30/84	
Project No: 3467	

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

PROJECT TITLE: PROCESS, PROPERTIES, PRODUCT RELATIONSHIPS
Z-Direction Velocity Measurements
Effect of Machine Variables on Paper and Board Properties

PROJECT STAFF: G. A. Baum

PROGRAM GOAL:

Develop relationships between critical paper and board property parameters and the way they are achieved as a combination of raw material selection, principles of sheet design and processing.

PROJECT OBJECTIVE:

To improve our capability of mechanically characterizing paper and board materials.

To relate measured parameters to end-use performance (especially in the case of Z-direction measurements).

To relate measured parameters to machine and process variables.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS LAST PERIOD: (April 1983 - September 1983)

1. The wet straining studies described in previous reports have been prepared for presentation at the TAPPI Paper Physics meeting in September.
2. Work on the relationships between in-plane and out-of-plane elastic parameters has continued, using different furnishes.
3. Work to improve our ability to measure out-of-plane elastic parameters have gone forward to the point where a wood grain cover report is in preparation.
4. A paper has been written for the Paper Physics meeting describing how to determine light scattering coefficients in dark and heavy basis weight materials.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

1. The effect of process variables on TEA and stretch at failure have been examined.
2. Work on the relationships between in-plane and out-of-plane elastic parameters has continued using different furnishes and refining levels.
3. A wood grain cover report has been written concerning our work to measure out-of-plane elastic parameters.

PROJECT TITLE: Process, Properties, Product Relationships	Date: 3/18/83
PROJECT STAFF: G. A. Baum	Budget: $105,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use.	Period Ends: 6/30/84
	Project No: 3467
PROGRAM AREA: Performance and Properties of Paper & Board	Approved by VP-R:

PROGRAM GOAL:

Develop relationships between critical paper and board property parameters and the way they are achieved as a combination of raw material selection, principles of sheet design and processing.

PROJECT OBJECTIVE:

To improve our capability of mechanically characterizing paper and board materials.

To relate measured parameters to end-use performance (especially in the case of Z-direction measurements).

To relate measured parameters to machine and process variables.

PROJECT RATIONALE:

It is important to understand the relationships between end-use performance and properties in order to improve paper and board products or maintain performance within close tolerances while utilizing available raw materials, minimizing energy requirements, and minimizing environmental impacts.

RESULTS TO DATE:

Ultrasonic techniques for measuring in-plane and out-of-plane elastic properties have been developed. A caliper gage has been designed and constructed to allow simultaneous measurement of caliper during Z-direction ultrasonic measurements. This caliper gage has been evaluated and found to be comparable or superior to other methods of accurately measuring caliper. The effects of fiber orientation, wet pressing, wet straining and drying restraints on the in-plane and out-of-plane properties of paper have been studied. The in-plane and out-of-plane elastic parameters have been related to end use tests and converting performance in a number of situations.

PLANNED ACTIVITY FOR THE PERIOD:

In-plane and out-of-plane elastic constants will be measured in a representative group of samples differing in composition and structure and in different ambient environments. These data will be compared with use-oriented test results, where possible. Particular attention will be given to tensile strength, stretch, TEA, and possibly tear.

Specific scattering coefficients will be measured in heavy board materials differing in composition and structure. These will be used to predict relative bonded area.

Work on ZD velocity measurements in thin and rough samples will continue. Improvements in the existing model should be possible.

POTENTIAL FUTURE ACTIVITIES:

The effort to establish relationships between properties and end-use performance is expected to continue.

STUDENT RELATED RESEARCH: M. Forbes, Ph.D.-1983; B. Pankonin, Ph.D.-1983; J. Deuser, M.S.-1983; C. Byl, M.S.-1983; T. Ave'Lallemant, M.S.-1983 B. Burger, M.S.-1984; P. Swodzinski, M.S.-1984.

but the results concerning yield or furnish type were inconclusive. A student, B. Berger, is doing A291 research to address the yield question. His results should be available in the next report.

We are still examining the results of the furnish studies discussed in the last report, using an alternative form of the equation above, viz. $R_{13} = R_{12}R_{23}$, where $R_{12} = C_{11}/C_{22}$, etc. We hope to present these in the next report as well.

(3) In Fleischman's thesis and in previous PAC reports we have discussed the effects of certain process variables (wet pressing, fiber orientation, and wet straining) on tensile strength, STFI compressive strength, and elastic properties. Recently we have gone back and looked at strain at failure and tensile energy absorption (toughness) or TEA. These results are presented in Section 2.

(4) At the last Paper Properties and Uses PAC meeting we discussed a possible automated, operator-proof, device for measuring in-plane elastic properties easily and quickly. This device has been designed and the components are currently being fabricated. The system operation will be controlled by an Apple computer. The Apple was chosen because of the existing machine language software needed for the cross-correlation method of determining ultrasound velocities. The new device will be described at the PAC meeting in March, and written documentation should be available in the next PAC report.

G. A. Baum
2/13/84

SECTION 1

PROCESS, PROPERTIES, PRODUCT RELATIONSHIPS

Z Direction Velocity Measurements

Project 3467

In past reports we have discussed the techniques which we developed for Z direction shear and longitudinal velocity measurements. These were a time-of-flight, neoprene platen, longitudinal measurement and a time-of-flight, "pillow" couplant shear measurement. We have now accepted these tests as standards, and we are not actively seeking further improvements. In this report, we discuss the inherent problems in measuring out-of-plane stiffnesses on thin and rough samples and give our interpretation of the results. We begin by stating our definitions of "thin" and "rough" and give a short discussion of what we are trying to determine in Z direction testing.

If the wavelength, λ, of ultrasound in the sample is greater than, or of the order of the caliper, then the sample is "thin." For our purposes, the thinness (T) is defined as λ divided by the neoprene caliper (ℓ_{SN}). Since wavelength decreases with frequency, it is best to use the highest possible frequency to effectively make the sample thicker. However, if the wavelength decreases to the order of the thickness of a fiber, then much of the ultrasonic energy is lost to scattering by the fibers, and ultrasound does not propagate well in the sheet. A proper frequency can be chosen to make a sheet "thick" if its caliper is much greater than the lateral dimension of its fibers. For sheets made of typical wood fibers, attenuation due to scattering becomes prohibitive at a few megahertz; therefore, our measurements are made from 0.5 to 1.0 MHz in the shear mode and from 1.0 to 2.0 MHz in the longitudinal mode. These are near the highest frequencies we can use without undue difficulties from scattering.

A sample is rough if the uncertainty in the location of its boundaries is not small compared to its caliper. On a microscopic level, the surface of a sheet is irregular. These irregularities can cause difficulties in coupling acoustic energy into the sheet and distortions in the meaning of the calculated velocity. Since neoprene platens conform to the surface of the sheet much better than hard platens, the difference between standard hard platen caliper (ℓ_{SH}) and neoprene caliper is an indication of surface irregularity. We use this difference divided by the neoprene caliper as a measure of roughness, i.e., "roughness" (R) is defined as $(\ell_{SH} - \ell_{SN})/\ell_{SN}$. If R is small, the complications from poor coupling and from ambiguous caliper definitions can be minimized.

Ultrasound velocity determinations are important because they are nondestructive measures of a mechanical property. More specifically, velocity depends on the elastic and inertial properties of the sample. For the ideal case of a plane wave, of the form $e^{i(\omega t - kx)}$, propagating along a principal direction of an orthotropic medium, the phase velocity, ω/k, is equal to $(C/\rho)^{1/2}$. Here, C is the elastic stiffness in the principal direction and ρ is the mass density. Thus, the phase velocity of a plane wave is a measure of specific stiffness, C/ρ. It is this quantity that we are trying to determine when we measure velocity. Any complication due to finite T or R that causes the measured velocity to differ from ω/k must be avoided or taken into account.

For phase velocity measurements, the effect from thinness can be theoretically calculated. That is we can mathematically relate the measured phase velocity (V_A) to the mechanical properties of the sample. To do this, the sample is assumed to be uniform, smooth-surfaced, and well-coupled to the delay lines; therefore, roughness and poor coupling are ignored. The result is the following relationship between V (defines as ω/k) and V_A, the measured phase velocity:

$$\frac{1}{V} = \frac{1}{V_A} + \frac{\text{PHASE}(E)}{\omega \ell_S} \quad . \tag{1}$$

Here E, which equals $4Z_T Z_S/[(Z_T + Z_S)^2 - e^{(-2ik_S\ell_S)}(Z_T - Z_S)^2]$ is a function of the impedance of the sample (Z_S), the impedance of the delay line (Z_T), the sample caliper (ℓ_S), and sample wave number (k_S). Notice that the second term in E is a sinusoid that decreases exponentially with ℓ_S. Depending on the value of the quantity in the exponential, this term can result in a positive or negative contribution to phase (E). In fact, as ω progresses it alternates with a period in ω of $\pi V/\ell$, since REAL$(k_S) = \omega V$. So as ω varies, this term causes $1/V_A$ to oscillate about $1/V$. For a large caliper, this term approaches zero because of the imaginary part of k_S. This oscillation in $1/V_A$ with ω can be thought of as a result of the interference between the component coming straight through the sample and those components reflected between the interfaces before entering the receiver. As ω changes the phase relationship between these components varies, and the combination has alternately more and less phase than the straight-through component. When the caliper is large, the multiple reflections are much more attenuated than the straight-through wave, and the effect is small.

The other term in E is frequency and caliper independent. Looking at E as ℓ_S approaches infinity, we can study the effect of this term.

$$\lim_{\ell \to \infty} E = \frac{4Z_T Z_S}{(Z_T + Z_S)^2} \quad . \tag{2}$$

In our case $Z_T >> Z_S$, so E simplifies to

$$\lim_{\ell \to \infty} E \approx \frac{4 Z_S}{Z_T} \quad . \tag{3}$$

Since Z_T is real, the phase of E can be approximated as

$$\lim_{\ell_S \to \infty} \text{PHASE}(E) \approx \text{PHASE}(Z_S),$$

and $1/V$ is larger than $1/V_A$ by the amount $\text{PHASE}(Z_S)/\omega\ell_S$. This term gives a phase shift to the receiver signal that is proportional to the phase of Z_S. As ℓ_S increases, the ratio of this phase shift to the phase shift due to propagation through the sample decreases, and its effect on V_A decreases. This term causes an overestimate of velocity which decreases in magnitute with $\omega\ell_S$. The phase of Z_S is not zero because of losses in the sample. In fact, $\text{PHASE}(Z_S) = 1/2\ \text{PHASE}(C)$, since $Z_S = (\rho C)^{1/2}$. This term originates from noncancellation of phase shifts when a signal is transmitted from delay line to sample and sample to delay line. A straightforward application of transmission line theory shows that there is a finite phase shift between a transmitted and an incident wave at the boundary between an elastic and a lossy medium. In addition, the phase shift from elastic to lossy medium does not cancel the shift from lossy to elastic medium, and a net phase shift is produced when a plane wave is transmitted through a lossy plate between elastic delay lines. When $Z_T >> Z_S$, the net phase shift approaches $-\text{PHASE}(Z_S)$.

For a thin, well-coupled sample, the inherent difference between V and V_A can be attributed to two phenomena: the interference from multiple reflections and a phase shift arising from the lossy nature of the sample. Both effects decrease as frequency and caliper increase. The interference term is reduced by loss in the sample, since multiple reflections are more attenuated than the straight-through wave. However, the second effect is proportional to the loss angle in the sample. Both of these produce a frequency dependence in the measured value of V_A.

This discussion was directed at phase velocity measurements. The time-of-flight considerations are somewhat different. Since time-of-flight measurements only look at the first half wave striking the receiver, multiple reflections are of concern only if the sample caliper is less than a quarter wavelength, T > 4.0. In this case, the first multiple reflection (which must pass through the sample two more times than the primary signal) could interfere in the first half cycle. The lowest frequency used is 0.5 MHz and the highest velocities encountered are about 600 m/sec; therefore, there is no need for any worry about multiple reflections in time-of-flight measurement when caliper is greater than 300 μm. The frequency of routine sample characterization is at least 1.0 MHz, and significant interference will occur only when T > 8; therefore, a more realistic lower caliper limit is about 100 μm.

The phase shift due to sample losses would be the same in time-of-flight as in phase velocity measurements. This is because the shift in the straight-through component is the same as in a multiple reflection. The ratio of the loss phase shift to the propagation phase shift is phase$(Z_S)/k_S \ell_S$. From our results with the McSkimmin method, we conclude that the loss tangent in paper is about 0.1. Assuming a maximum ZD velocity of 600 m/sec, we find that the error from this term is less than 2% at 1.0 MHz if the caliper is over 200 μm.

From the above considerations, we conclude that time-of-flight measurements on paperboard samples are not significantly affected by multiple reflections or loss phase shifts. However, there are other problems. The shape of the signal in the first half cycle is sensitive to higher order Fourier components in the signal. Further into the pulse, where phase velocity measurements are conducted, the wave can be thought of as a pure sinusoid at the carrier frequency. However, the form of the first half cycle can be distorted by frequency-dependent attenuation and phase velocity in the sample. Relative phase shifts and amplitude shifts between Fourier components as the signal passes through the sample will deform the front edge of the signal. Since attenuation in paper increases with frequency, we expect this dispersion effect to be operative; however, it is difficult to quantify. The dispersion-generated error would be frequency dependent; most likely it would increase in magnitude rapidly with frequency.

The experimental results will lead us to conclude that roughness complications are the most important. This is discussed in detail later. However for the moment we merely state that roughness is like the other difficulties in that it causes a frequency dependent variation in the measured velocity.

Most of the data we discuss will be from a 26 lb/1000 ft^2 corrugating medium. This is a very rough sample and the results are difficult to rationalize. In order not to give the reader an unduely pessimistic view of the technique, we first present data from a well-behaved sample. This is a 110 lb/1000 ft commercial bleached kraft stock (mcs). It is about 700 μm in caliper and the depth of its rough surface interface is small compared to its caliper. Figure 1 is a plot of longitudinal ZD velocity for the MCS sample as a function of frequency. As frequency increases, there is a detectable increase in measured velocity. However, the variation is only a few percent, and the results from this sample are relatively frequency independent. The constancy of the measured velocities with varying frequency is taken as an indication of their validity. This is a sensible criterion, since all conceivable complications result in frequency dependent errors. Since the MCS values are stable, the ZD longitudinal velocity is taken as a good measure of the specific elastic stiffness of this sample.

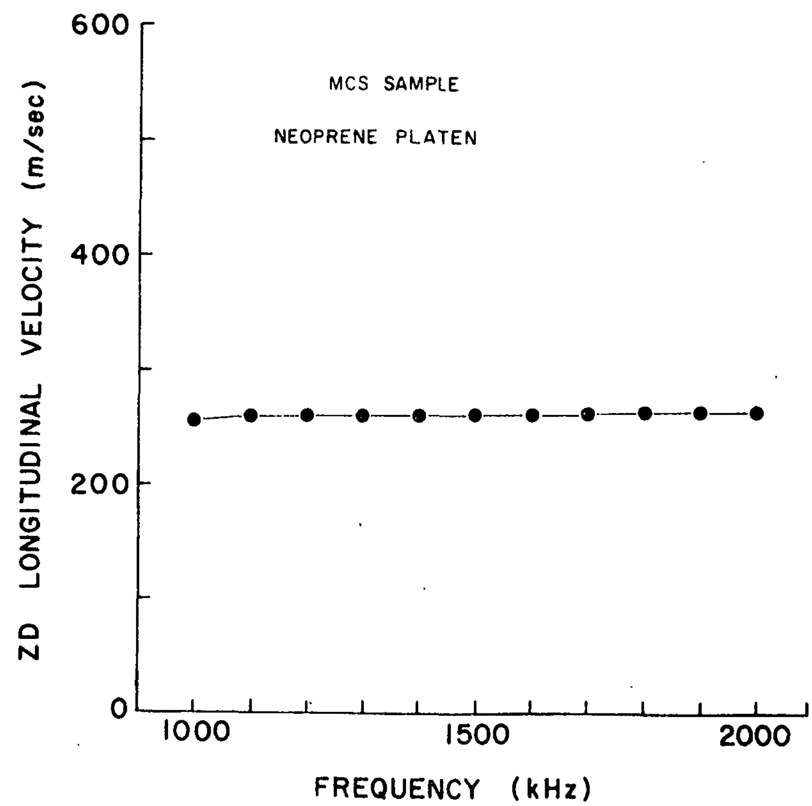


Figure 1. Neoprene platen, ZD longitudinal velocities vs. frequency for a machine-made bleached kraft paperboard. Hard caliper = 705 µm; neoprene caliper = 692 µm; R = 0.019.

Now consider the ZD shear velocity for the MCS sample. Figure 2 shows the three different measures of ZD-CD shear velocity. Notice first the phase velocities (pk. 3,4,5); they seem to oscillate with a small amplitude and constant period around a value of about 350 m/sec. This is consistent with the notion of multiple reflections causing oscillations in the measured phase velocities. From theory, the period in frequency of this oscillation should be $V/2\ell_s$. If this period is taken from the data, V can be roughly calculated. Using an estimate of 0.27 MHz for the period, V is found to be 380 m/sec. Within the uncertainty of the period measurement, this is about the same as the 350 m/sec average. We conclude that V is near 350 m/sec, and that V_A is oscillating about this value due to interferences from multiple reflections. There is not a steady decrease in V_A with frequency, suggesting the phase shifts from sample loss must not be important. The data is behaving as if only multiple reflections are causing V_A to differ from ω/k_s. As expected, the hard platen time-of-flight data (pk. 1) do not show these oscillations. In this case the value of T is much greater than 1/4 and multiple reflections are not a problem. Since phase shifts from losses do not affect V_A, they should not affect pk. 1 values. However, the velocities do increase with frequency, perhaps reaching a plateau at 365 m/sec. This frequency dependence must be due to dispersion or roughness. At any rate, by the time the standard frequency of 1.0 MHz is reached, the pk. 1 values are stable and very near the V_A results. We conclude that the shear velocities at measured 1.0 MHz are good measures of specific stiffness. Notice that the pillow values are always a few percent above the pk. 1 values, presumably because pillow calipers are a few percent less than hard platen calipers. The frequency effect is the same in pillow and hard platen data, indicating that roughness is not the cause. This conclusion is also supported by the lack of obvious roughness effects in V_A.

Now that we have seen what can be expected in a reasonably smooth and thick sample, we will examine the 26 lb/1000 ft^2 corrugating medium. It is relatively thin (about 190 μm), and the roughness factor is around 0.25. Figure 3 is the

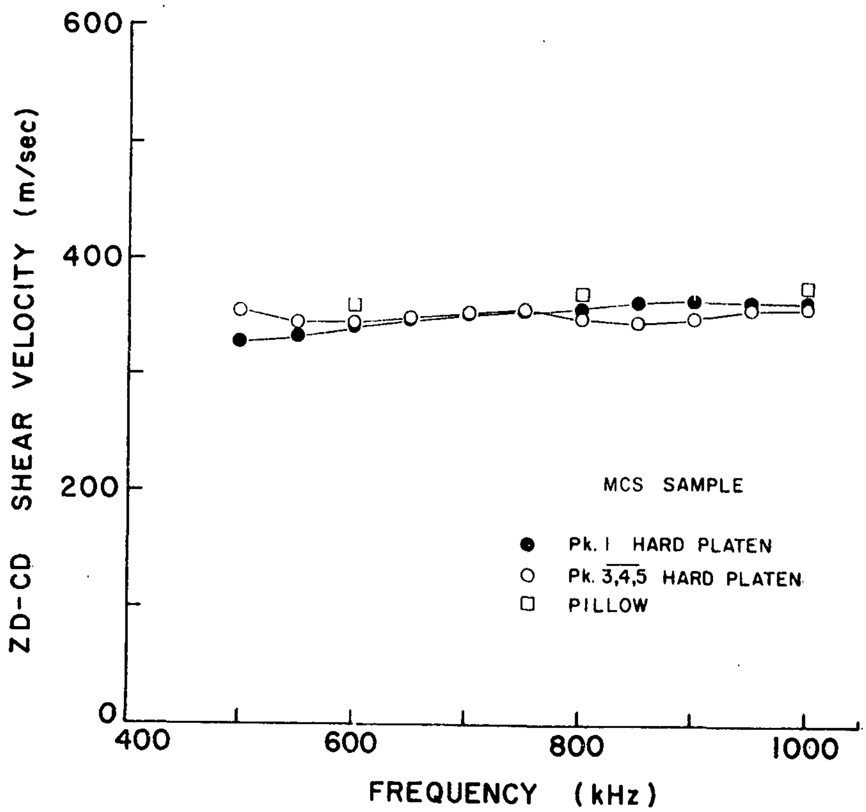


Figure 2. ZD-CD shear velocities vs. frequency for the MCS sample. Hard platen time of flight, pillow time of flight, and hard platen pk. 3,4,5 data are shown.

ZD-MD hard platen shear data vs. frequency for the unground CC76 at four pressures. We observed a rapid increase in signal amplitude with increasing pressure. All data are taken at one typical location on the sample. Notice that the variance of velocity with frequency is up to 20%. Oscillations in velocity with frequency also occur, especially at the lower pressures. There is a disconcerting decrease in velocity with pressure. In fact, the actual transit times increase with pressure even though the caliper is decreasing. The velocities at lower pressure seem unrealistically high.

The pillow data for the same sample are shown in Fig. 4. Here the signal amplitude was observed to increase slowly with pressure. The velocity varia-

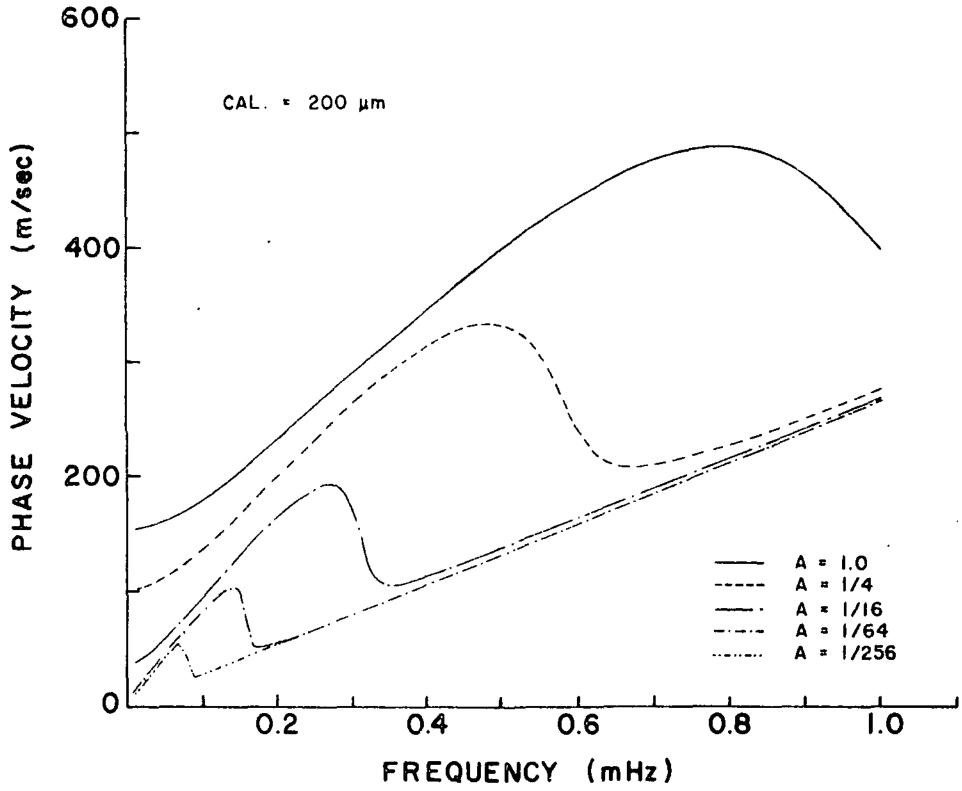


Figure 11. The same plots as Fig. 10 but for a 200 μm thick sample.

The best way to realize what is happening in the case of the unground medium is to look at it under a microscope. Shives, bundles of unpulped fibers, are scattered throughout the sheet. The extreme extensions of the surfaces are projections of these rigid inhomogeneities. When hard platen transducers are placed on the medium at low pressure, we presume (as shown in Fig. 12) that the transducer to sheet contact occurs only through the shives. The coupling is so poor that little signal is received. The small signal is selectively channeled, however, through the shives, which have a higher velocity than the bulk of the sample. As pressure is increased (or when pillow coupling is used), the amount of bulk material contacting the transducers increases such that the signal amplitude grows, but a smaller portion passes through the shives. In fact, a transit time increase with pressure can be rationalized if the total signal is thought of as an interference between two signals, one part channeled through the shives and the other through the bulk. At low pressure only the part channeled through the shives is present and velocity is large. At higher pressures, this signal is swamped out by the part concentrated in the bulk, and the first signal peak occurs later (even though caliper has decreased) and the velocity can actually decrease.

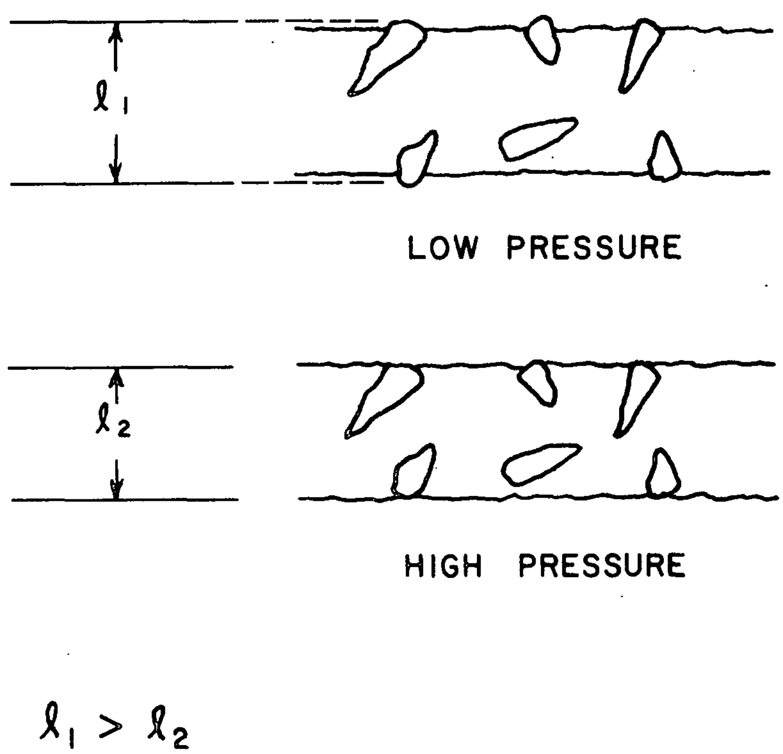


Figure 12. Idealized model of surface characteristics of a rough paper sample.

Some features of the picture can also be incorporated into a three transmission line model. As before, the interface region will be less dense than the interior, but now the velocity is made greater in the interface. In this way we can model a rough and rigid surface. Figures 13, and 14 use the same bulk properties as the model curves shown in Fig. 10 and 11, but the interface regions are given a velocity of 2000 m/sec. In Fig. 13 and 14, curves for a sheet with no surface layers are included for reference. Notice that the interface region can result in a larger apparent velocity than obtained for the reference if A is not too small. The effect of changing A in Fig. 13 and 14 is roughly to project the curves along straight lines through the origin. From Fig. 14, we see that the large velocities can be achieved by increasing the surface depth. The anomalously large phase velocities found experimentally, and their decrease in severity with improved coupling, is repeated qualitatively in Fig. 14. The experimental increase in oscillation frequency with poor coupling, however, is not a feature of theoretical curves. This transmission line model displays some of the characteristics of the phase velocities found for the unground medium samples, but it is not as successful as the rough homogeneous theory was for the ground medium.

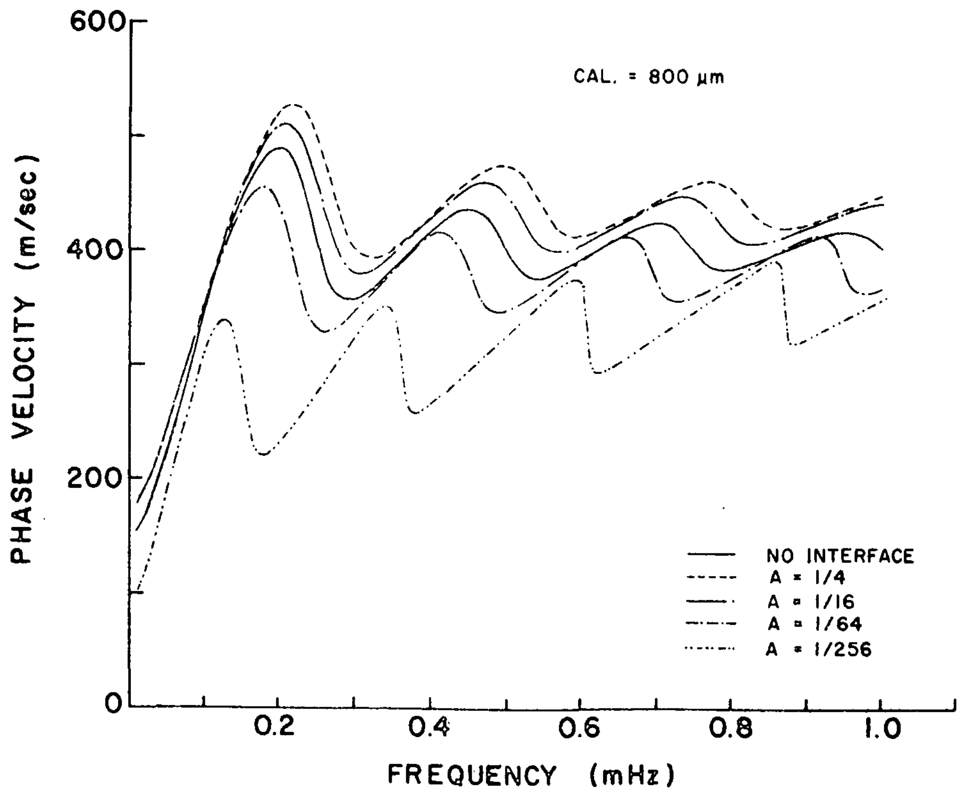


Figure 13. Theoretical plots of the apparent phase velocity vs. frequency for a 800-µm sample whose interior phase velocity is 400 m/sec and surface phase velocity is 2000 m/sec. ρ = 600 kg/m^2, ℓ_I = 40 µm, tanδ = 0, $\rho_I = A\rho$, and $2\ell_I + \ell_S$ = 800 µm.

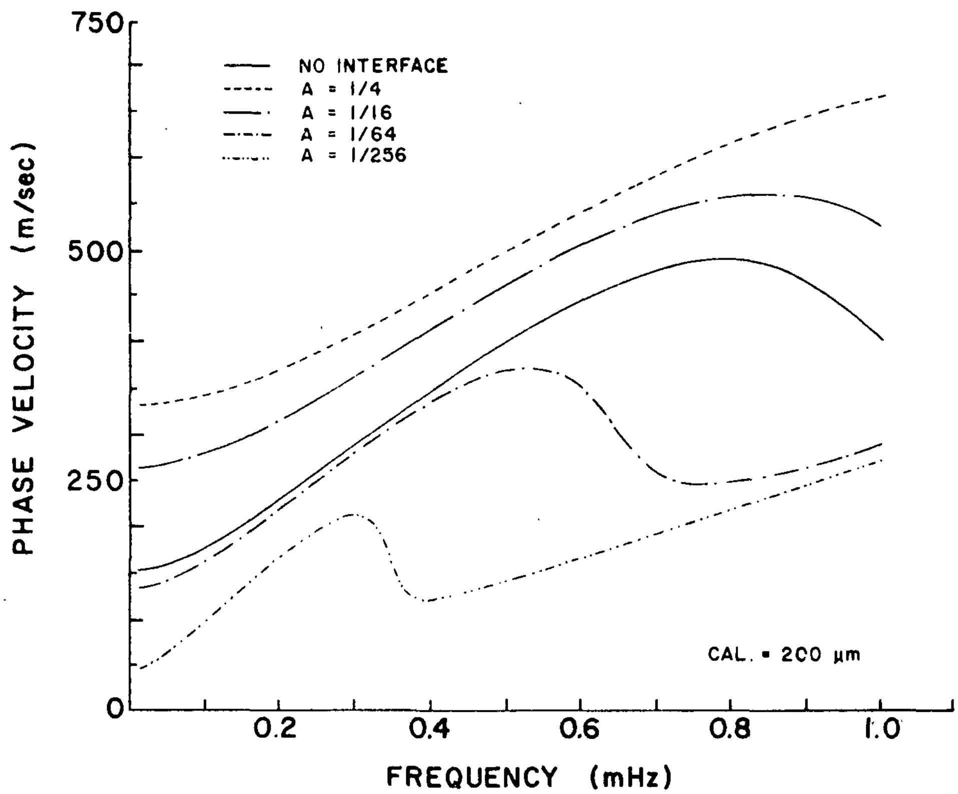


Figure 14. The same plots as Fig. 13 but with caliper of 200 µm.

Based on the previous arguments we can now estimate the limits on sample properties that assure valid ZD velocity measurements. Thinness can result in multiple reflection interferences and reduced resolution because of the smaller transit times. For the time-of-flight methods used here, these problems are not serious until caliper is under 100 µm. Therefore, caliper should be at least 100 µm before we can assume that the velocity is a good measure of an average intensive property of the sheet. Roughness, in most cases, is the limiting factor. From our experience, we feel that the R factor (hard caliper minus neoprene caliper divided by neoprene caliper) must be less than 0.1 to avoid serious distortions in the measured velocities due to poor

Figure 15 is an example of how C_{33} (E_Z) is influenced by wet pressing (density) and wet straining. The figure has been slightly rotated about the Z-axis and tipped forward. The rear of the figure is the behavior with wet pressing (density) with no wet straining. Wet straining reduced C_{33} and also the density.

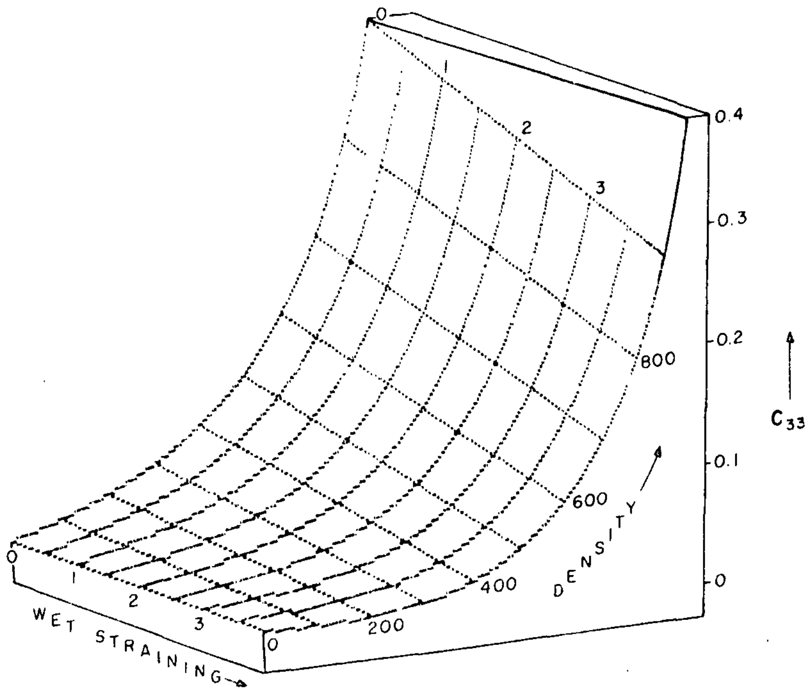


Figure 15. The effects of wet straining and density (wet pressing) on the out-of-plane elastic stiffness, C_{33}.

This report describes additional work studying the effects of the same machine variables on two other important sheet properties, breaking strain at failure and tensile energy absorption.

Strain at Failure

Figure 16 shows the MD strain at failure vs. IPC density. The MD failure strain (MD stretch) is seen to be only slightly sensitive to fiber orientation, decreasing slightly as fiber orientation is increased. Wet straining, however, has a large effect. At a density of 700 kg/m^3, for example, the 2.4% wet strain (high) produces a decrease in MD stretch from about 3 to 1.7%. Furthermore, at the low wet strain (0%) MD stretch increases with density (wet pressing), whereas at high wet strains MD stretch is decreasing with density. Figures 17 and 18 show how MD stretch varies with wet straining and density, at two levels of fiber orientation. At a low fiber orientation (not random) (Fig. 17) the MD stretch is independent of density at the highest wet straining level. At the higher fiber orientation (Fig. 18) this condition is reached at the intermediate wet straining level (about 1%). At the highest wet straining level the MD stretch decreases with increasing density. The order in which the variables are applied are the same as on the paper machine at about the same moisture levels. Thus wet straining follows wet pressing. It appears that at high fiber orientations and high wet straining levels, the sheet may be damaged such that MD stretch decreases, even through MD tensile may still be increasing.

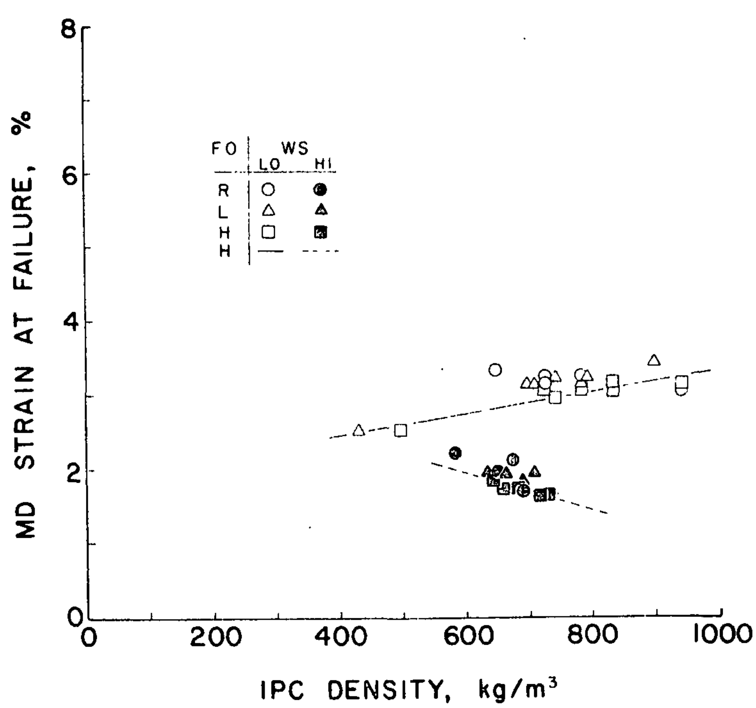


Figure 16. MD strain at failure vs. IPC density.

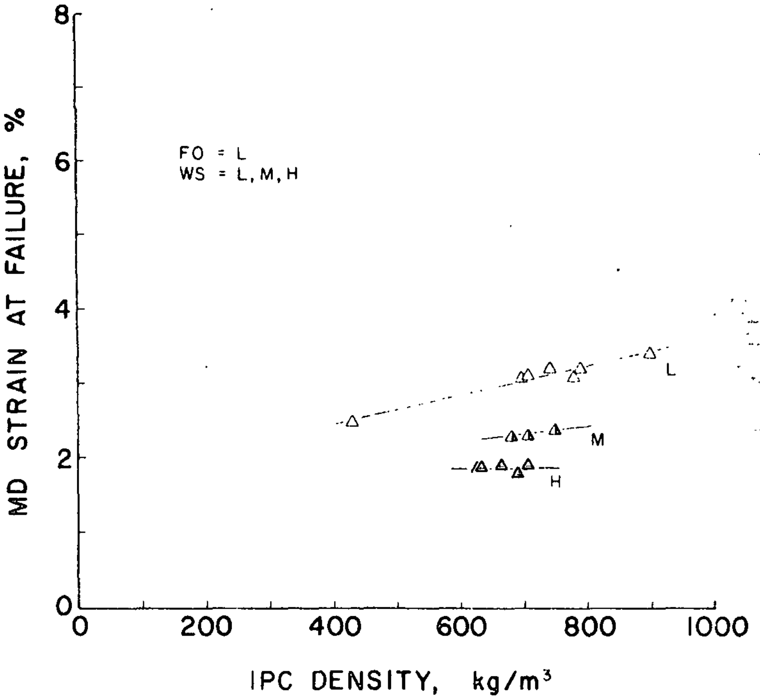


Figure 17. MD strain at failure vs. IPC density.

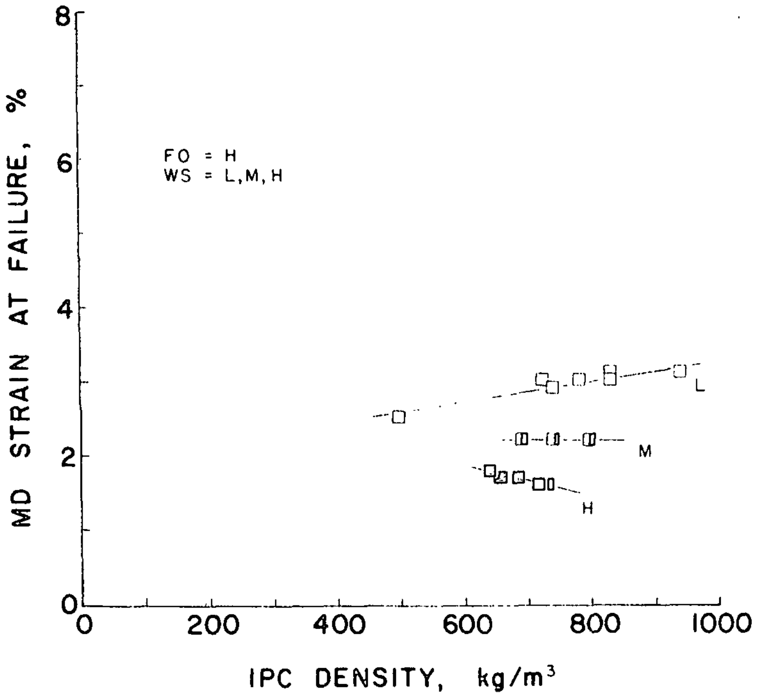


Figure 18. MD strain at failure vs. IPC density.

Figure 19 shows CD strain at failure vs. density. Here we see the opposite trend. As we might expect, CD stretch seems to increase only slightly with increasing (MD) fiber orientation, and increases 25 to 30% with an increase in (MD) wet straining. CD stretch increases with density at all fiber orientation and wet straining levels. These results are summarized in Table II.

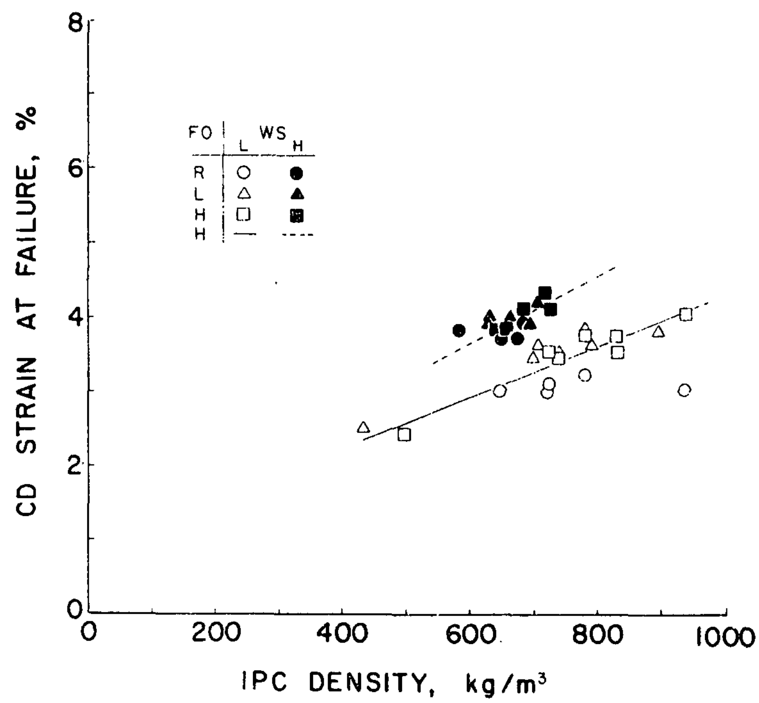


Figure 19. CD Strain at failure vs. IPC density.

TABLE II

EFFECT OF MACHINE VARIABLES ON STRETCH AND TEA

	Fiber Orientation (MD)	Wet Pressing	Wet Straining (MD)
MD strain to failure	- (small)	+(lo WS), -(hi WS)	- (large)
CD strain to failure	+ (small)	+ (all WS)	+ (large)
MD TEA	+ (large)	+	- (large)
CD TEA	- (large)	+	+

Several authors have used the idea of studying process changes by looking at "failure envelopes" or plots of tensile strength vs. stretch at failure (Seth, et al., Tappi 65(3):135(1982)). Figure 20 shows such failure envelopes for a number of conditions of fiber orientation, wet straining, and density. (On each curve, density increases in moving from bottom to top.) In general, large increases in tensile strength are achieved by increasing fiber orientation, while wet straining has a much lesser effect. Wet straining, however, produces substantial decreases in MD stretch. Figure 20 suggests that papermakers should be able to achieve almost any combination of MD tensile strength and MD stretch in the range shown by controlling the three variables named.

Figure 21 shows CD tensile strength vs. CD stretch using the same scales as in Fig. 20. The relative roles of MD fiber orientation and MD wet straining are

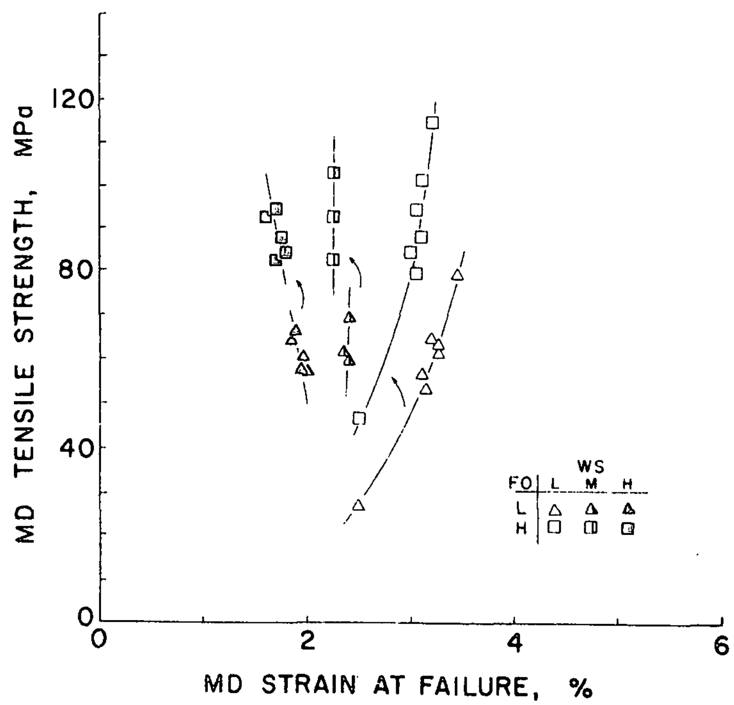


Figure 20. MD tensile strength vs. MD strain at failure.

reversed here. Fiber orientation decreases CD tensile and does not affect stretch very much. Wet straining also has a large negative effect on CD tensile but also increases CD stretch.

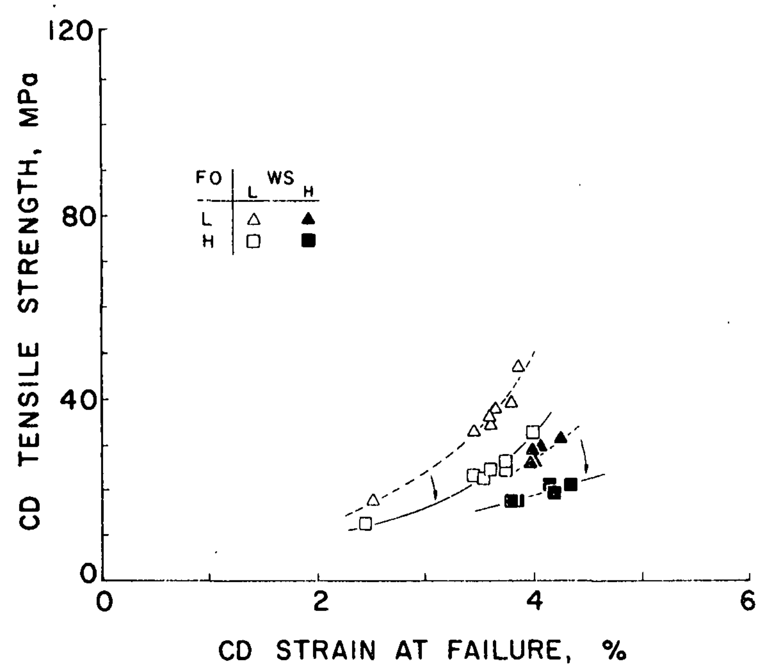


Figure 21. CD tensile strength vs. CD strain at failure.

Figure 22 shows both MD and CD tensile strength vs. MD and CD stretch, as influenced by MD fiber orientation and density. Figure 23 gives MD and CD tensile strength vs. MD and CD stretch as influenced by MD wet straining and density. The conclusions drawn from these last two figures, of course, are the same as those stated earlier. The collective effects of fiber orientation, wet pressing, and wet straining can produce large differences in tensile strength and breaking strain (and other properties). Figure 24 is the same as Fig. 23, but a constant density line of 700 kg/m^3 has been added to help interpret the role of wet pressing.

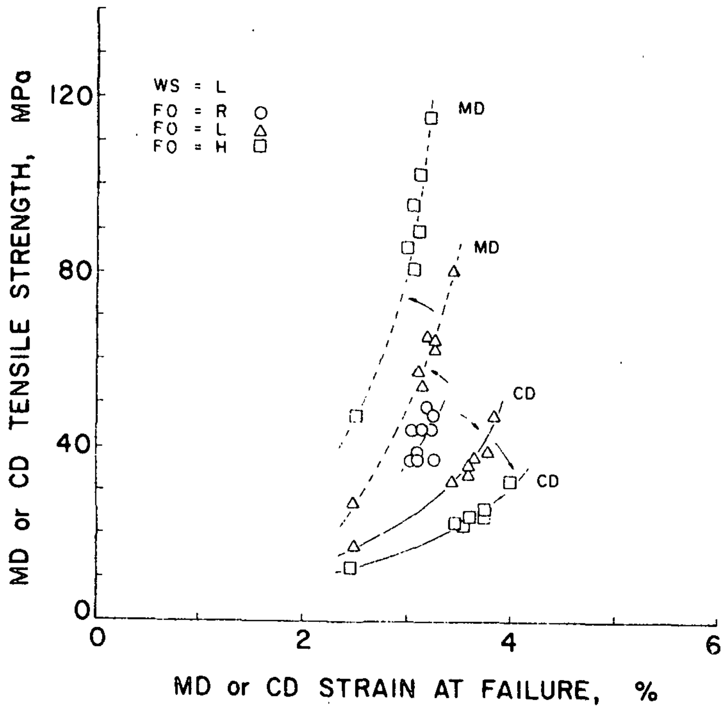


Figure 22. MD or CD tensile strength vs. MD or CD strain at failure.

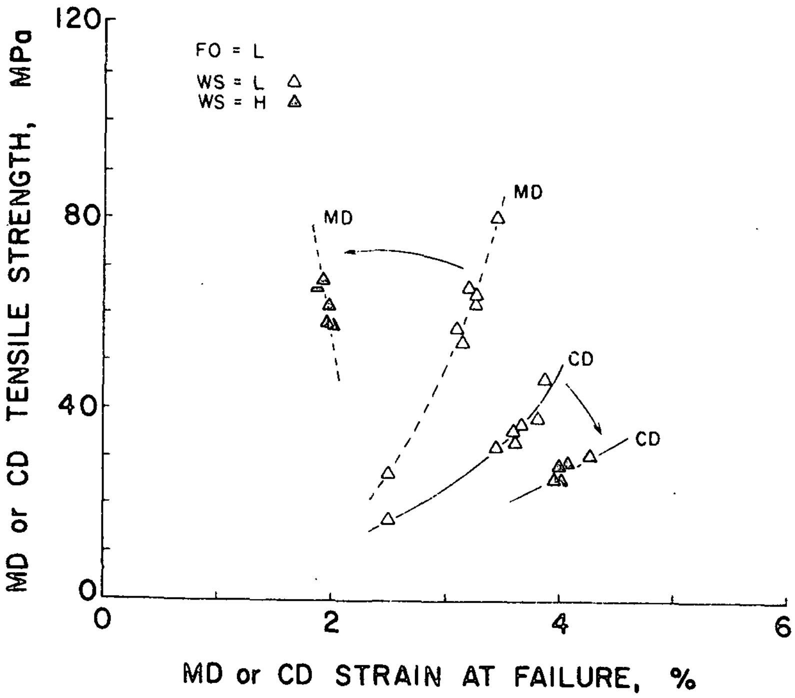


Figure 23. MD or CD tensile strength vs. MD or CD strain at failure.

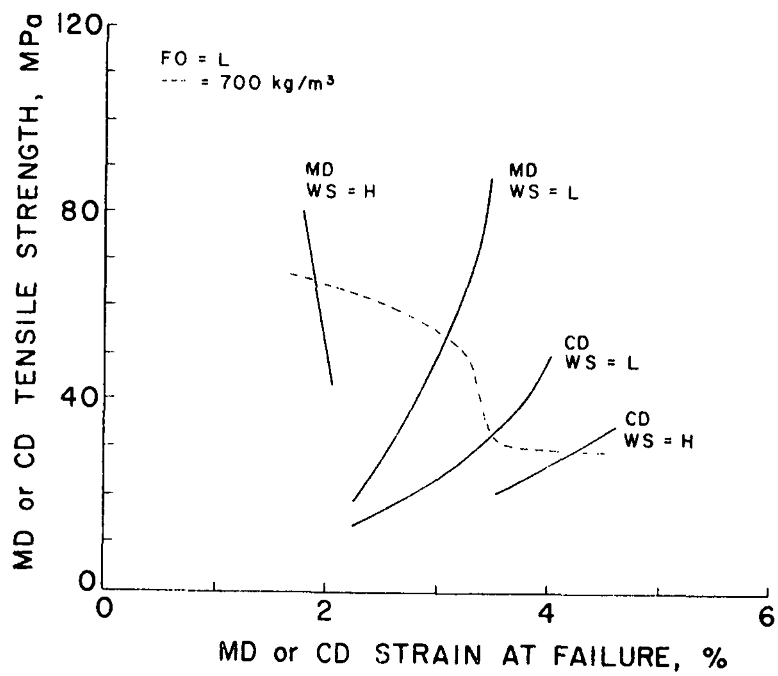


Figure 24. MD or CD tensile strength vs. MD or CD strain at failure with constant density line of 700 kg/m^3.

Tensile Energy Absorption (TEA)

TEA (or toughness as it is called in other fields) is the area under the load-elongation curve. It is thus clearly related to both breaking stress and elongation at failure, as well as initial modulus and the "shape" of the stress strain curve. Figure 25 shows MD-TEA vs. IPC density at a low fiber orientation and several levels of wet straining. Wet straining in the MD clearly reduces MD TEA and reduces its sensitivity to density changes as well. Figure 26 is similar but depicts a higher MD fiber orientation level. MD TEA is increased with increased fiber orientation, but the sensitivity to wet straining is enhanced. A two percent wet strain produces about a 25 to 30 percent decrease in TEA. Wet straining also seems to alter the behavior with densification, for TEA seems to be slightly decreasing with increased density at the higher wet strain levels used (1.2 and 2.4%).

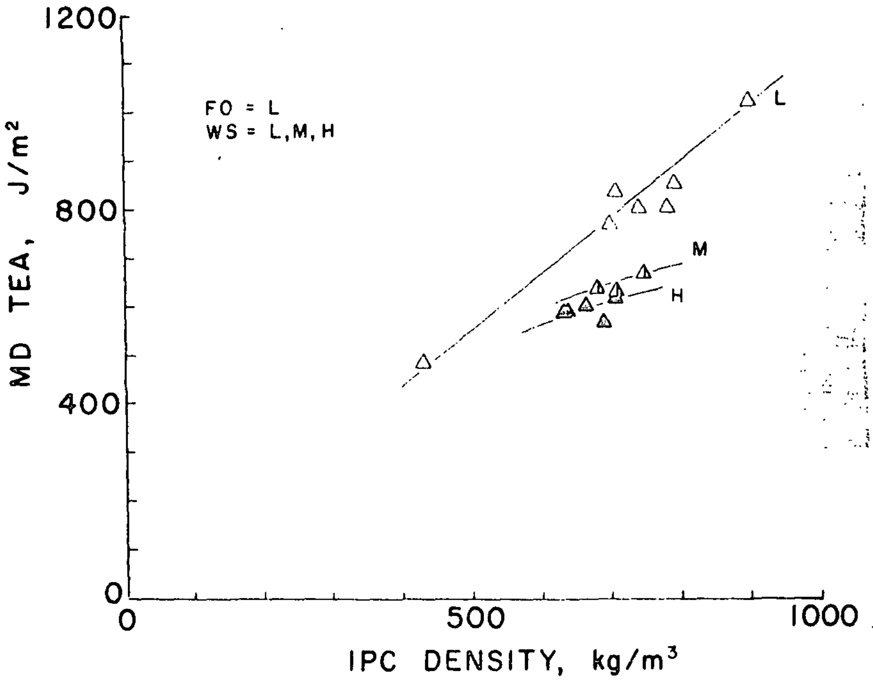


Figure 25. MD TEA vs. IPC density.

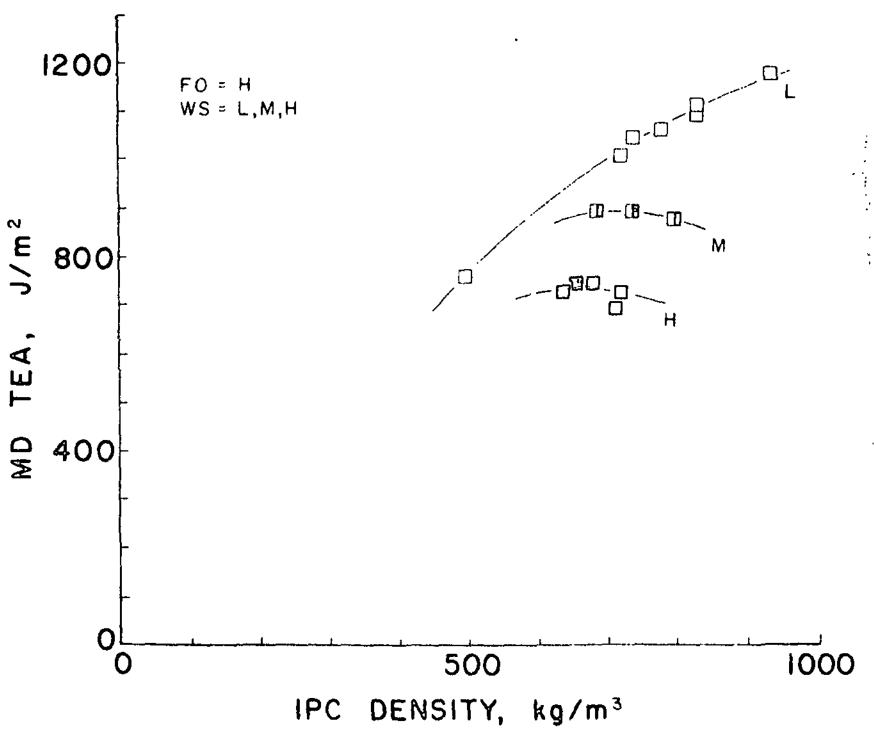


Figure 26. MD TEA vs. IPC density.

Figure 27 depicts CD TEA vs. IPC density. In this case increase MD fiber orientation decreases TEA while wet straining at either fiber orientation tends to increase CD TEA.

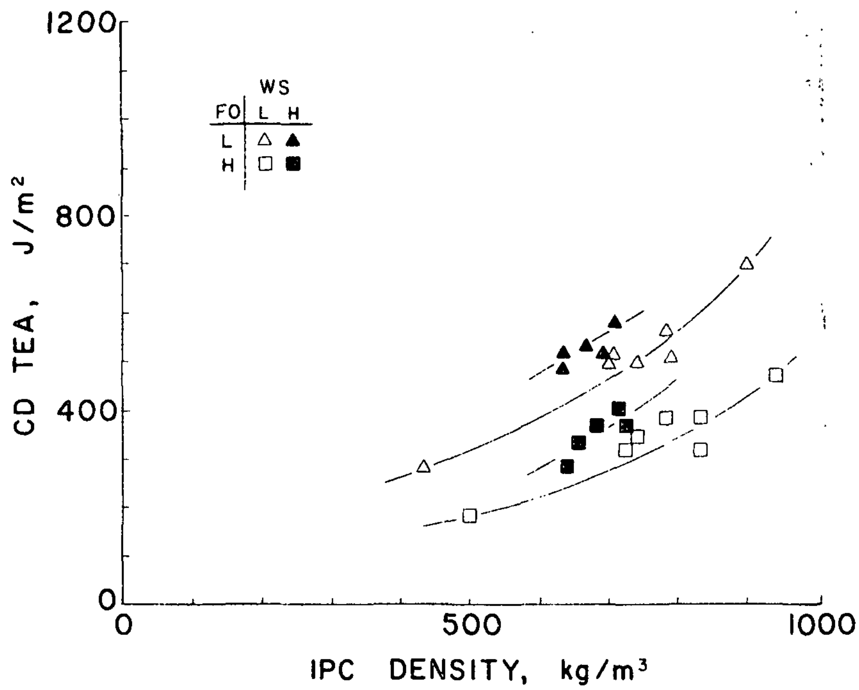


Figure 27. CD TEA vs. IPC density.

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

Date:	Feb. 18, 1984
Budget:	$75,000
Period ends:	6/30/84
Project No.:	3332

PROJECT TITLE: ON-LINE MEASUREMENT OF PAPER MECHANICAL PROPERTIES
Analysis of Off- and On-Line Data on Linerboard
FKBG Contract Research: Mill Worthy Sensor

PROJECT STAFF: G. A. Baum/C. C. Habeger

PROGRAM GOAL: Develop ways to measure and control manufacturing processes

PROJECT OBJECTIVE:

To develop the capability to measure certain elastic parameters on a moving paper web. Current emphasis is on in-plane measurements on low basis weight papers and on out-of-plane measurements.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS LAST PERIOD: (March 1983 - September 1983)

1. The FKBG sponsored project concerned with evaluations of a mill worthy sensor were discussed in the September report. There has been much interest by papermakers in this work, and it now appears that AccuRay and Measurex, the two licensees, are beginning to develop hardware.

2. The on-line sensor designed for measurements on low basis weight sheets (described in the status report, dated March, 1983) is being successfully used to monitor changes in the mechanical properties of corrugating medium due to preconditioning.

3. A new technique has been developed to ascertain transit times in the paper web which avoids tedious data gathering and calibration procedures. The technique uses a single transmitter and two receivers at two different distances from the transmitter. A cross-correlation technique is used to determine the delay time. This procedure requires no calibration of the system to account for non-paper delay times. The technique is being successfully used on our laboratory measurement system (in-plane) and also with the low bais weight sensor alluded to above. Those people with in-plane ultrasonic systems based on the IPC design, who would like to use this new technique, can obtain the software (for Apple II) by contacting C. C. Habeger or G. A. Baum at IPC.

4. Preliminary on-line measurements of z-direction stiffness are encouraging. This activity was described in the September 1983 report.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

1. Results of an analysis of preliminary data show that mill velocities and laboratory velocities correlate quite well. The moisture and correction formulae were evaluated, as well, but at present the data is insufficient to properly assess their accuracy.

2. The FKBG activity is discussed in Section 2. The electronics console was returned to IPC in November so several problems could be corrected. This has now been returned to Valdosta. We hope to start testing again in March.

3. A comprehensive report for FKBG is in preparation.

4. The proposed DOE project concerned with on-machine measurements and process control is expected to be funded by late summer.

5. An automated in-plane laboratory system has been designed and is presently being fabricated.

Date: 3/18/83	
Budget: $75,000	
Period ends: 6/30/85	
Project No.: 3332	
Approved by VP-R: [signature]	

PROJECT TITLE: On-Line Measurement of Paper Mechanical Properties

PROJECT STAFF: G. A. Baum/C. C. Habeger

PRIMARY AREA OF INDUSTRY NEED: Properties related to end uses

PROGRAM AREA: Control of manufacturing processes

PROGRAM GOAL: Develop ways to measure and control manufacturing processes

PROJECT OBJECTIVE:

To develop the capability to measure certain elastic parameters on a moving paper web. Current emphasis is on in-plane measurements on low basis weight papers and on out-of-plane measurements.

PROJECT RATIONALE:

The ability to measure certain mechanical properties on the paper machine is valuable from several standpoints. It provides a potential means for vastly improved process variables. It provides a non-destructive way to assess product quality on a continuous basis, since certain mechanical properties are correlated with common paper specifications.

RESULTS TO DATE:

Developed theory of ultrasound propagation in paper and developed device for measuring paper and board in-plane elastic parameters on-machine. Successfully tested device in mill environment. Constructed rugged version for extended testing in linerboard mill (contract research). Constructed and tested a version useful for light weight grades which is also self calibrating.

PLANNED ACTIVITY FOR THE PERIOD:

(1) We intend to initiate studies to explore the feasibility of making out-of-plane ultrasonic measurements on a moving paper web. Several approaches will be examined in laboratory tests. Successful approaches will require the construction of suitable hardware for on-line testing. The electronics package for any out-of-plane system will be quite different than for the in-plane measurements.

(2) A cross correlation technique for in-plane measurements will be investigated. This would have a number of advantages over present techniques.

POTENTIAL FUTURE ACTIVITIES:

Investigate possible control strategies on the paper machine to control measured parameters.

SECTION 1

ON-LINE MEASUREMENT OF PAPER MECHANICAL PROPERTIES

Analysis of Off- and On-Line Data for Linerboard

Project 3332

Laboratory ultrasonic tests were conducted on Owens-Illinois linerboard samples from seventeen reels manufactured between October 6 and October 17, 1983. The laboratory results were compared with the on-line ultrasonic velocity measurements. The purposes of this test were (1) to access the performance of the on-line velocity gage, (2) to refine the "dead time" calibration values, and (3) to evaluate the moisture and temperature correction formulae.

The performance of the on-line gage (apart from a constant calibration error) was judged from the correlation of the mill velocities (corrected for moisture and temperature) to the laboratory velocities (made at standard conditions). Figure 1 presents a plot of the MD mill velocity vs. the laboratory MD velocity. Notice the correlation coefficient is 0.93, indicating that the on-line gage is a good predictor of laboratory sonic velocity. The 5% error bar on the laboratory data comes from the typical standard deviation in laboratory measurements. Using this as an estimate of uncertainty in the velocity of sound in paper, we can argue that within experimental error the laboratory and mill data are linearly related. Figure 2 is an identical plot for the shear velocities. Here the variation in velocity between samples is not much greater than the 5% uncertainty, making it difficult to judge the on-line values. The correlation coefficient is 0.6, which is about all one can expect when scatter due to sheet non-homogeneity is nearly as large as the reel to reel variation.

The performance of the moisture and temperature correction formulae were evaluated by checking the correlation of moisture with V_L/V_m and temperature

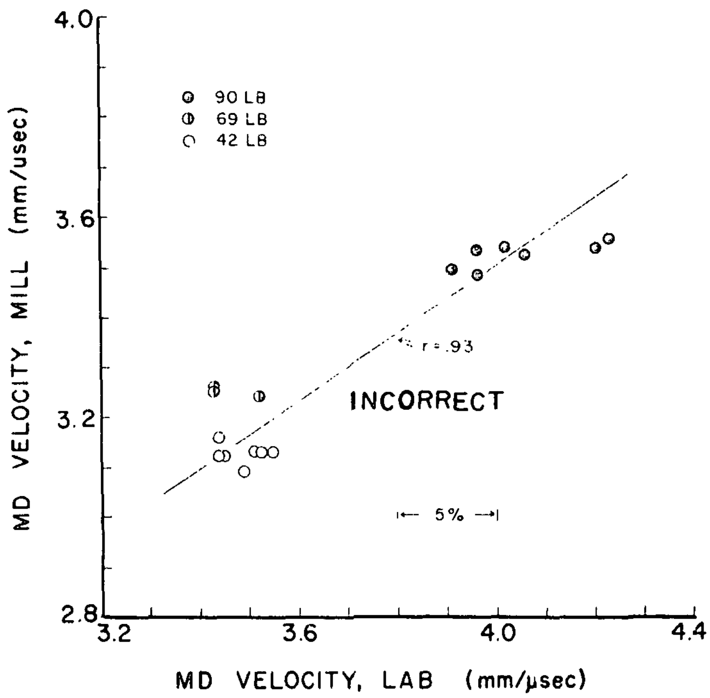


Figure 1. MD mill velocity vs. the laboratory MD velocity.

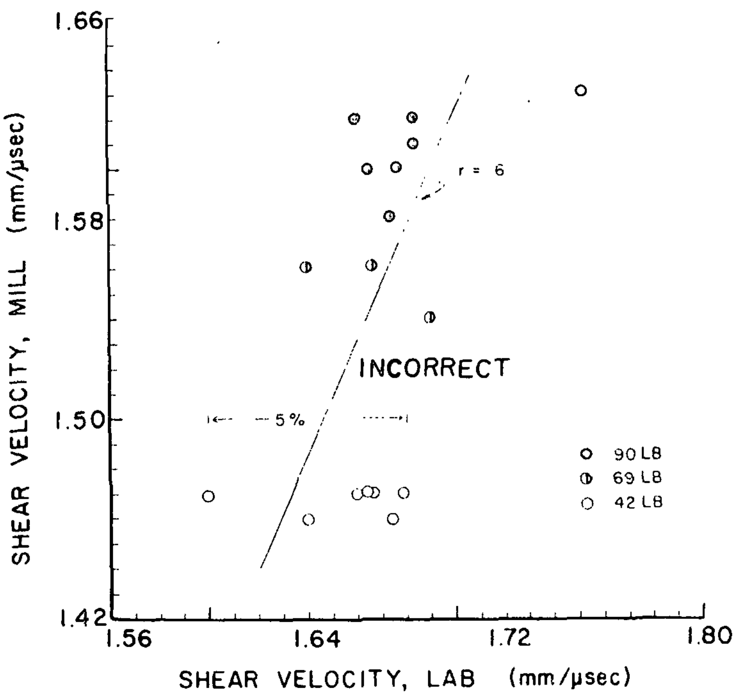


Figure 2. Shear mill velocity vs. laboratory shear velocity.

with V_L/V_m. The correlation coefficient was very small in each case as hoped for [R (moisture) = -0.12 MD and -0.13 shear, while R (temperature) = -0.032 MD and -0.35 shear]. The negative sign suggests that there may be an overcorrection for both moisture and temperature, but the correlation coefficients are so small that little significance can be given to any correction using this data. The same "problem" of consistent product from reel to reel confounded this test as it did the others. Over the seventeen samples, moisture varied only from 5.2% to 6.5% and temperature from 198°F to 207°F. Clearly, to make significant statements about anything (other than the data time correction), we need more data with wider variations in mechanical properties, reel moisture, and sheet temperature. We will collect more data in our spring mill trials.

SECTION 2

ON-LINE MEASUREMENT OF PAPER AND BOARD MECHANICAL PROPERTIES

FKBG Contract Research: Mill Worthy Sensor

Project 3332

INTRODUCTION

The objective of this project is to design, construct, and test an on-line sensor capable of measuring linerboard properties under mill operating conditions. The sensor should be rugged and reliable, and capable of measuring on-machine tensile or shear stiffnesses on basis weights above about 125 gm/m^2 and speeds up to 2500 fpm.

A sensor meeting the above criteria has been operating on a linerboard machine (Owens-Illinois, Valdosta, GA) since early January, 1983. The sensor hardware, electronics, and associated software have been described extensively in a previous FKBG report, dated September 8-9, 1982. The initial mill experience and mill test results were reported in FKBG report dated March 3-4, 1983. In the latter report we noted that the values of specific tensile and shear stiffnesses measured on-machine could be used to predict CD ring crush and bursting strength.

In the last report (September 28-29, 1983) moisture and temperature correction capabilities were discussed, correlations were established on a broader data base, and strength parameters were predicted and displayed on the Measurex CRT.

The overall objectives of the project have been met. (1) The device has operated with no major problems for a period of ten months. (Nearly all problems during this period have been with electronic equipment due to the hot and humid mill environment. These difficulties may be easily remedied.)

(2) Correlations between stiffness parameters and strength parameters have been established. Just as important, if not more so, the measured stiffnesses can be used to monitor the papermaking process continuously, thus allowing appropriate changes if linerboard properties begin to deteriorate.

Recent Activity

The electronics console was returned to IPC in November, 1983, because of difficulties with the microprocessor. As before, the problem seemed to be related to corrosion of contacts on the circuit card. While this problem was being remedied we also cleaned and repaired the air conditioning system. This had failed during a hot August and most likely influenced a number of the other problems in the electronics. The unit was shipped back to Valdosta in January. Testing for the 1984 research program will begin in February.

Prior to the electronics problem in November, Measurex had been gathering data to compare the values of ring crush and bursting strength measured on-machine to the respective values measured in the test lab in the mill. They indicate they will share their results with us, but as yet we have not received any information. We do know that the correlations to date have been very good.

General Observations

As noted in the last report, changes in the specific extensions and shear stiffnesses with changing machine conditions will make the device useful as a process control sensor. At present the measured parameters give an immediate assessment of product quality. The machine operators have reportedly learned to use these outputs to advantage, however, in adjusting the machine.

The on-line sensor technology has been licensed to both AccuRay and Measurex and prototype instruments are expected in six months to one year. Inquiries as to the availability of a device should be directed to these two companies.

Future

The work planned for 1984 includes (1) correlations between on-machine measurements of stiffness with off-machine strength measurements, (2) changes in measured stiffnesses with changes in machine variables, and (3) preparation of a comprehensive report.

Item (1) is of particular importance, of course, and will be the most time consuming for the reasons given in the September 28-29, 1983 report.

Item (2) will have to be agreed upon by the mill operating personnel and management. The preparation of a comprehensive report is underway.

As we have said before, we believe the real potential of the device will be as a process sensor to control the paper machine.

G. A. Baum
1/16/84

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3500

SHEAR DEFORMATION AND FAILURE

(Formerly Mechanical Testing in Shear)

February 10, 1984

Date:	March 18, 1984
Budget:	$70,000
Period Ends:	6/30/84
Project No:	3500

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

PROJECT TITLE: MECHANICAL TESTING IN SHEAR
(Formerly Mechanical Testing in Shear)

PROJECT STAFF: J. F. Waterhouse

PROGRAM GOAL:

Develop relationships between the critical paper and board property parameters and the way they are achieved as a combination of raw material selection, principles of sheet design and processing.

PROJECT OBJECTIVE:

The objective is to improve methods for evaluating the in-plane and out-of-plane shear characteristics and other related mechanical properties of paper and board, and to relate these properties to end-use performance, sheet composition, structure (machine and process variables), and the effects of moisture and temperature. We wish is to understand how the choice and location of materials in the web and the papermaking process affects properties, and to what extent they can be controlled to enhance the paper or boards converting characteristics, i.e. runnability and post conversion properties.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS PAST PERIOD: (March 1983 - September 1983)

(1) Some of the results reported in earlier status reports and a wood grain cover report has been prepared for presentation at the TAPPI Paper Physics Conference in September.

(2) Torsion shear measurements and ultrasonic shear measurements have been made and compared with shear measurements made at FPL on the same material.

(3) Out-of-plane shear strength measurements made in simple shear (IPC and FPL) gave values slightly lower (about 25%) than the calculated value from the IPC torsion measurements.

(4) A study has been initiated to investigate variations in properties due to variations in ZD restraint during drying.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

(1) Work is continuing on the variation of in-plane drying stresses in the Z-direction. This is discussed in the attached report.

PROJECT TITLE: Mechanical Testing in Shear	Date: 3/18/83
PROJECT STAFF: J. F. Waterhouse	Budget: $70,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use	Period Ends: 6/30/84
PROGRAM AREA: Performance and properties of paper and board	Project No: 3500
PROGRAM GOAL:	Approved by V-R:

Develop relationships between the critical paper and board property parameters and the way they are achieved as a combination of raw material selection, principles of sheet design and processing.

PROJECT OBJECTIVE:

To improve methods for evaluating the in-plane and transverse shear characteristics and other related mechanical properties of paper and board, and to relate these properties to end-use performance, sheet composition, structure (machine and process variables), and the effects of moisture and temperature. Our objective is to understand how the choice and location of materials in the web, and the papermaking process affects these properties, and to what extent they can be controlled to enhance the paper or boards converting characteristics, i.e. runnability and post conversion properties.

PROJECT RATIONALE:

We believe that both in-plane and out-of-plane properties are important to such converting processes as corrugating, molding, creasing, scoring and other forms of out-of-plane shape modification. Many converting operations involve high shear and bending stresses beyond the elastic regime. Successful converting is often quite dependent on the ability of the sheet to resist shear and bending. Research is needed to develop adequate shear test methods for characterizing the load-elongation behavior, especially at failure.

RESULTS TO DATE:

Investigated several methods for measuring the stress-strain behavior in out-of-plane shear. Studied effect of shear straining on compressive strength. Studied variation of properties in the Z-direction.

PLANNED ACTIVITY FOR THE PERIOD:

1) Design and build equipment for measuring the out-of-plane shear deformation behavior of paper and board under both static and dynamic conditions An improved mounting procedure will also be incorporated to reduce the time for sample preparation.

2) Determine the effects of composition and papermaking process variables on the out-of-plane viscoelastic properties of paper and board under different environmental conditions.

POTENTIAL FUTURE ACTIVITIES:

Determine the out-of-plane deformation behavior of paper and board when subjected to various combined stress situation, e.g. normal (Z-direction) and out-of-plane shear stresses.

Status Report

SHEAR DEFORMATION AND FAILURE

Project 3500

INTRODUCTION

A number of important factors have emerged from our work on the measurement of the shear deformation behavior of paper and board using the torsion method. These include the variation of both in-plane and out-of-plane properties in the thickness direction of paper and a possible related causal factor; a variation of drying or internal stress in this direction. We believe that an understanding leading to control of these factors is important with respect to the converting and end-use properties of paper and board. In our last report we presented some preliminary results of a technique to directly measure the variation of drying stress in the thickness direction of paper and we expect to continue work in this area. We have also been actively involved in evaluating an approach developed by Htun (1) of STFI for the indirect measurement of drying stresses in paper using stress relaxation measurements.

We believe that the shear deformation measurements made to date represent a modest beginning and further work is required to determine the nature of interfiber bond failure in a fiber assembly and the effects on it of raw materials and papermaking variables. The measurement of viscoelastic properties employing the shear mode is also of importance and some preliminary studies have been made to determine how this might be accomplished.

The change in the title of this project is a reflection of the broader implications of the work undertaken so far and to direct some of our effort towards an understanding of the failure mechanisms associated for example with the runnability of paper and board and the complex stress situations to which they might be subject during converting and end use.

<u>The Variation of In-Plane Drying Stress in the Thickness Direction of Paper</u>

An important contribution to this work is being made by Dr. Sławomir Stera of the University of Łódz, Poland, whose three month visit to IPC is being funded by an international scholarship exchange program (IREX).

Deformation properties (e.g. elastic and failure) of paper are vitally dependent on a given set of conditions (i.e. furnish, refining, fiber orientation and wet pressing) and on the type of restraint applied during drying. Without restraint, a paper web will normally undergo a certain amount of shrinkage when it is dried. This is mainly attributed to a large shrinkage in the cross section of the fiber, which in a fiber network manifests itself at interfiber bonds. If this shrinkage is partially or wholly prevented (i.e. the sheet is restrained during drying) it is possible to measure an associated drying stress. An improvement in both elastic and strength properties is normally found with an increase in drying stress. This is illustrated in Fig. 1 where the variation of MD specific elastic modulus with MD specific drying stress for various levels of fiber orientation and drying restraint is shown using the data of Fleischman (2).

The viscoelastic nature of the wet web implies that the manner in which it is dried (i.e. its moisture and temperature history) can be expected to influence the level of drying stress. The work of Htun (1) has shown this to be the case as his results reproduced in Table I indicate. The importance of drying conditions on board properties was noted by Htun. However, the relevance of his work to our present investigation is the possible variation of in-plane drying stress in the thickness direction and the attendant change in properties.

We have reported (October Status Report) on a technique to directly measure

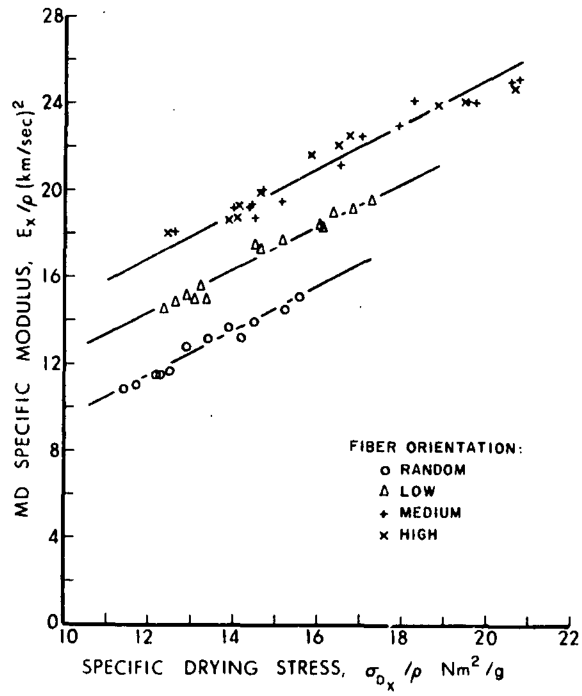


Figure 1. Variation of elastic modulus with drying stress.

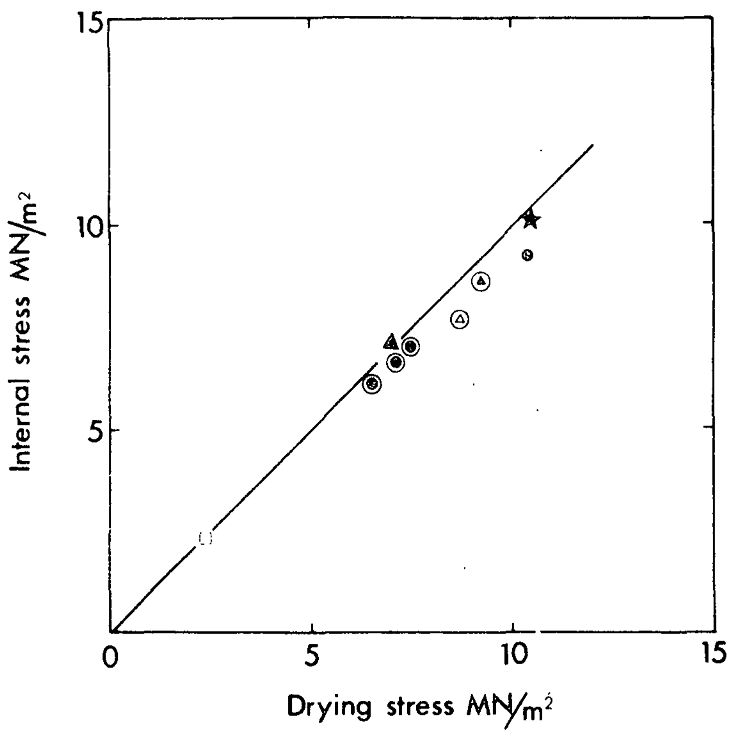
TABLE I

THE INFLUENCES OF DRYING CONDITIONS ON THE MECHANICAL PROPERTIES*

Drying temp. °C	Drying time min	Specific final drying stress kNm/kg	Specific elastic modulus MNm/kg	Tensile index (spec. tensile strength) kNm/kg	Strain to failure %
30	2.5	8.9	10.3	120	3.4
	8	7.6	9.0	89	2.6
	25	7.4	8.2	90	2.9
50	2.5	7.3	8.3	96	2.9
	8	6.5	7.5	87	2.7
	25	5.6	7.0	76	2.8
80	2.5	6.1	7.2	88	3.0
	8	5.6	6.9	81	2.6
	25	5.2	6.7	72	2.3

*Data of Htun (1)

the variation of drying stress in the thickness direction of paper and expect this work to continue. In our current work we are attempting to indirectly measure drying stress using stress relaxation measurements. Htun (1) has proposed that the internal stress in paper is equal to the external drying stress as shown in Fig. 2. He employs stress relaxation measurements and interpretations given in earlier work by Kubat (3) to determine internal stress levels.



*Internal stress versus drying stress: * = beaten to 50°SR, o = beaten to 43°SR, whole pulp. ⓞ = first beaten to 43°SR and later fractionated. Sheets containing different fiber fractions: Δ = beaten to 21°SR wet-pressing 0.45 MPa, Ⓐ = beaten to 21°SR - wet-pressing 1 MPa, Ⓐ = beaten to 21°SR - wet-pressing 2 MPa, □ = unbeaten pulp.*

Figure 2. Equivalence of internal stress and drying stress taken from Htun (1).

Basically Kubat argues that the slope F of the linear portion of the stress-log time curve should be a linear function of the applied initial stress

σ_0. Furthermore, the intercept on the stress axis should be equal to the internal stress. Therefore in principle we should be able to measure the variation of drying stress in the thickness direction by measuring the variation of internal stress. This idea was originally proposed by Wiley (4).

To explore this possibility samples of commercial 42 lb linerboard have been prepared to make stress relaxation measurements in both the machine and cross directions on the whole board and on felt, wire and middle sections of the board which have been produced by surface grinding. Characterization of these samples will include basis weight, caliper, and in-plane and out-of-plane ultrasonic measurements.

Average properties for sixteen whole board samples are shown in Table II. The results of stress relaxation measurements for the whole board in both the machine and cross directions are shown in Fig. 3. Regression equations give values of internal stress of 7.72 Nm/g and 1.56 Nm/g for the machine and cross directions respectively.

TABLE II

CHARACTERIZATION OF COMMERCIAL 42 LB LINERBOARD
(Avg. 16 Sheets)

Sample	Basis Weight g/m2	Cal (mm) IPC	Density g/cm^3	ν_{xy}	ν_{yx}	E_x	E_y	G	E_z	R
Avg.	207.5	0.287	0.723	0.176	0.431	10.47	4.263	2.513	0.0459	2.47
S.D.	1.699	0.0038	0.0139	0.0328	0.0537	0.3078	0.3062	0.0636	0.00156	0.212
%CV*	0.82	1.35	1.92	18.6	12.5	2.94	7.18	2.53	3.40	8.58

*CV = coefficient of variation

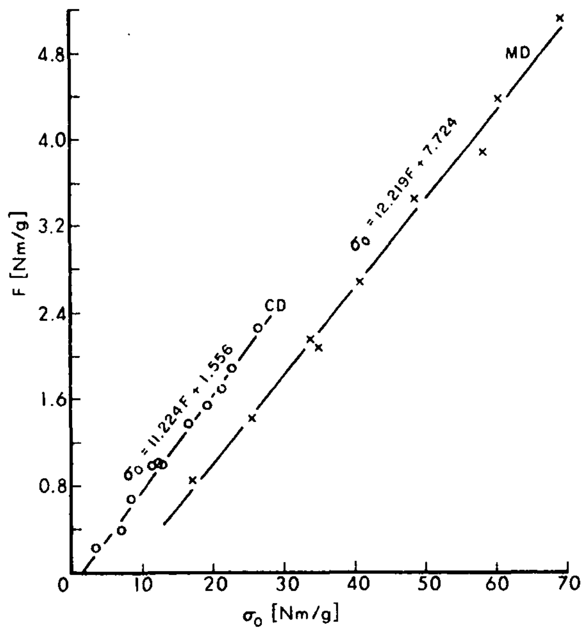


Figure 3. Internal stress determination for 42 lb linerboard.

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1. Htun, Myat. The influence of drying strategies on the mechanical properties of paper. Doctor's Dissertation. Stockholm, Sweden, STFI, 1980.

2. Fleischman, Elmer H., Jr. An investigation of the elastic and dielectric anisotropy of paper. Doctor's Dissertation. Appleton, Wisconsin, The Institute of Paper Chemistry, 1981.

3. Kubat, Joseph. A similarity in the stress relaxation behavior of high polymers and metals, Collected Papers, Stockholm, Sweden, STFI, 1965.

4. Wiley, James H. An investigation of drying stress variation through the thickness of paper. A200 Problem 299A, The Institute of Paper Chemistry, June 16, 1982.

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3470

FUNDAMENTALS OF DRYING

February 10, 1984

PROJECT SUMMARY FORM

DATE: February 14, 1984

PROJECT NO. 3470 - Fundamentals of Drying

PROJECT LEADER: Fred Ahrens

IPC GOAL: Reduction of the "necessary minimum" complexity (number and/or sophistication) of process steps.

OBJECTIVE:

Develop an understanding of the physical mechanisms controlling the removal of water from a moist web under various boundary conditions typical of proposed new concepts and use this knowledge to identify drying conditions that may result in reduced energy use, utilization of low-grade energy, increased drying rates, and/or a favorable impact on paper properties. Evaluate the potential of advanced-concept drying systems.

CURRENT FISCAL BUDGET: $150,000

SUMMARY OF RESULTS SINCE LAST REPORT: (October, 1983 - January, 1984)

High intensity drying performance and mechanisms have been investigated for an intermediate range of mechanical pressures (5-300 psi). The drying rate increases more rapidly with pressure at high pressure levels, suggesting the possible importance of liquid water removal as the impulse drying regime is approached. Vapor pressure measurements at these conditions confirm that a large driving force (e.g., 10-100 psi) for liquid and vapor flow is available in the sheet at high surface temperature and mechanical pressure operating conditions.

Total water removal and liquid water removal have been measured over a range of impulse drying conditions, for surface temperatures up to 800°F. It is found that, under high pressure and temperature conditions, more than 40% of the total water removal from a 100 g/m^2 sheet can occur in the liquid phase. This has significant energy implications.

A tentative paper grade/furnish/properties test matrix has been prepared to aid in the broad, systematic evaluation of advanced water removal processes. Using this matrix as a standard test set, a technical data base will be developed through tests over a range of operating conditions.

PROJECT TITLE: Fundamentals of Drying	Date: 3/18/83
	Budget: $150,000
PROJECT STAFF: F. Ahrens	Period Ends: 6/30/84
PRIMARY AREA OF INDUSTRY NEED: Capital effectiveness.	Project No.: 3470
	Approved by VP-R:

PROGRAM AREA: Reduction of process complexity.

PROGRAM GOAL: Reduction of the "necessary minimum" complexity (number and/or sophistication) of process steps.

PROJECT OBJECTIVE:

Develop an understanding of the physical mechanisms controlling the removal of water from a moist web under various boundary conditions typical of proposed new concepts and use this knowledge to identify drying conditions that may result in reduced energy use, utilization of low-grade energy, and/or increased drying rates. Evaluate the potential of advanced-concept drying systems.

PROJECT RATIONALE:

Driers are one of the major consumers of energy in pulp and paper mills, and they are very capital-intensive. Improving conventional drying systems could only slightly reduce the large energy requirements. Therefore, new drying concepts that lead to reduced energy usage and faster water removal are needed.

Many proposed and potential drying concepts use boundary conditions totally different from those in conventional drying systems, so the present knowledge base of conventional drying will not be directly applicable. To identify and evaluate new drying concepts, an understanding of the fundamentals of water removal from moist webs under these new conditions is required.

RESULTS TO DATE:

The drying rate of 42 lb/1000 ft^2 handsheets has been measured, for broad ranges of hot surface temperature and applied mechanical pressure, at both atmospheric and thermally-induced vacuum ambient conditions. Drying rates up to ten times conventional rates have been observed. Even when surface temperatures below conventional levels are employed, thermal/vacuum drying rates up to four times conventional rates are observed.

The drying mechanisms under these "high intensity" drying conditions have been investigated through detailed experimental measurements (e.g., instantaneous heat input rate, internal web temperatures, vapor pressure at hot surface) and through mathematical modeling and analysis at various levels of detail. Improved understanding of high-intensity and thermal/vacuum drying has resulted from this activity.

The construction of a small-scale, heated roll apparatus for the investigation of impulse and high-intensity drying under moving web conditions is nearly complete.

PLANNED ACTIVITY FOR THE PERIOD:

The moving web apparatus will be used in the investigation of high-intensity and impulse drying. Hybrid impulse-thermal/vacuum drying experiments will be performed. Experimental and analytical investigation of the high-intensity and thermal/vacuum drying mechanisms will be continued. Analysis of the potential benefits of advanced concept drying systems will be performed. The related project work on impulse drying will be coordinated with the goals of this project.

POTENTIAL FUTURE ACTIVITIES:

The design of a versatile continuous moving web test bed for the demonstration, development and performance evaluation of advanced concept drying systems will be pursued.

FUNDAMENTALS OF DRYING

INTRODUCTION

It seems surprising that a mature technology such as paper drying has a large potential for improvement. However, the high-intensity drying processes which are under investigation at The Institute of Paper Chemistry have indeed demonstrated great potential. Drying systems using these high-intensity processes will be significantly smaller and, hence, less costly than conventional systems, or they will allow increased production rates. Also, they will be more energy efficient. Impulse drying appears to have the greatest potential for reducing energy use, due to a thermally-induced liquid-phase dewatering action. Thermal/vacuum drying has potential for using low-grade, less-expensive energy, due to the reduced boiling point resulting from vacuum operation. Furthermore, these water removal methods may, through beneficial effects on paper properties, lead to improved products or perhaps new products. They should permit given product specifications to be achieved with a reduced quantity or quality of raw material. This would yield a further energy savings.

Most of the work to date in the project has been directed toward investigating the technical feasibility of high-intensity water removal processes and establishing a level of understanding of their mechanisms. In some of the most significant accomplishments we have:

1. Shown that impulse drying (a hybrid pressing/drying concept) can give two to three orders of magnitude greater drying rates and use much less energy (30 to 70%) than conventional drying.

2. Shown that thermally-induced vacuum drying can give an order of magnitude increase in drying rate and can use low-grade energy for drying.

3. Defined the heat and mass transfer mechanisms for high-intensity drying processes (including press drying, thermal/vacuum drying, and impulse drying):

- developed several experimental devices for drying studies.
- established a technique for measuring instantaneous heat flux to the paper and made other detailed measurements needed to understand and quantify the performance of high-intensity drying.
- developed successful mathematical models of high-intensity drying processes.

The primary objective of future work in this project is to extend the current understanding of high-intensity water removal principles to include the comprehensive data base required for their effective and efficient commercial application. Drying performance and paper properties data for a representative range of paper grades and fiber furnishes are needed for engineering studies, overall economic assessment, and to enable matching the various high-intensity concepts with proper applications. Technical questions relating to the design of water removal systems using these high-intensity processes must be answered. In addition, an overall technology assessment of the potential of advanced water removal systems is needed.

In this report, the elements of the overall plan for this project will first be reviewed. Then, results of recent and current work in the project will be presented. This will include presentation of a tentative paper grade/furnish/property test matrix which has been selected as a standard test set for characterizing and assessing advanced water removal processes, including both pressing and drying. Finally, the goals and plans for the next reporting period will be summarized.

LONG RANGE PLAN

Improved understanding, additional technical data, and technology assessments are needed to guide the development and application of the high-intensity drying principles investigated thus far in this project, and to encourage successful commercialization of water removal systems based on these principles. The nature of the data and assessments needed to allow commercialization to proceed, and the tasks required to produce this information, have been reviewed. Based on these considerations, a long-range plan for the project has been formulated.

A diagram exhibiting the key elements of the project, and their interrelationships, is given in Fig. 1. For completeness, both past and future areas of effort are included. A brief description of the objectives of these project elements is as follows.

1. Exploratory and Feasibility Studies:

   Provide early information (via bench-scale experiments) on the technical feasibility of improving the water removal process by application of high-intensity concepts such as impulse drying and thermal/vacuum drying. Quantify the potential benefits of these concepts.

2. Investigation of Water Removal Mechanisms:

   Develop an understanding (via bench-scale experiments and mathematical modeling) of the heat and mass transfer processes governing water removal from the paper web under high-intensity operating conditions typical of impulse drying, thermal/vacuum drying, etc., to provide a basis for guiding the development and design of advanced water removal systems.

3. Technical Performance Data:

   Develop a base of technical data (still by means of tests at the bench scale) on drying performance, energy use, paper properties, etc., for a representative range of paper grades, fiber furnishes and operating conditions sufficient for identification and assessment of advanced water removal system opportunities.

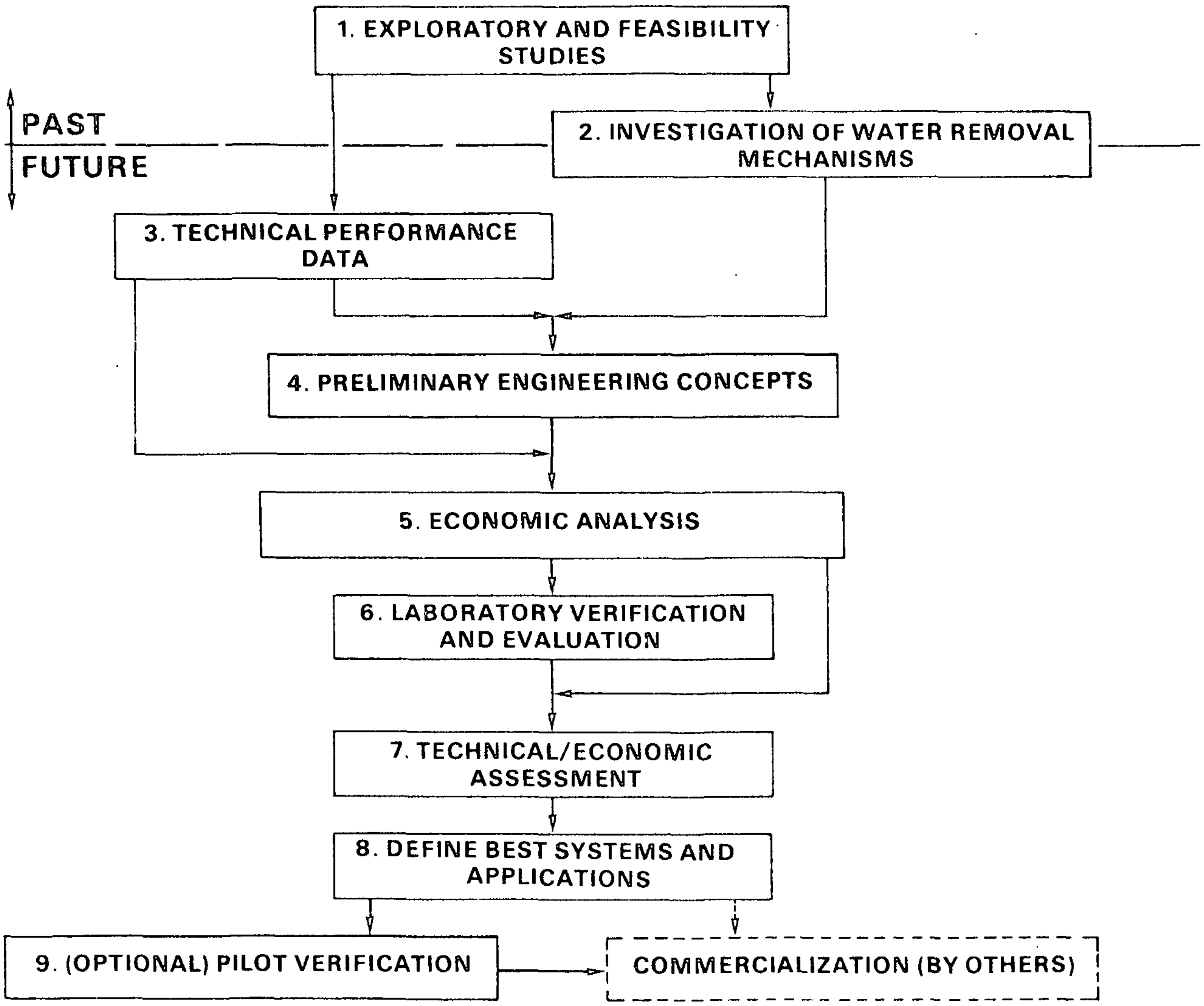

Figure 1. Long-range project elements.

4. Preliminary Engineering Concepts:

   Utilize the technical data gathered in Task 3 to establish preliminary system configurations (i.e., hardware requirements, size estimates, heat source options, etc.) appropriate for the various paper grades.

5. Economic Analysis:

   Develop capital and operating cost estimates for the various system concepts which are applicable to each paper or board grade and select those applications worthy of future work. This analysis should include the mill-wide impact of higher drying rates, smaller equipment, and use of different energy forms and rates.

6. Laboratory Verification and Evaluation:

   For the most promising systems and grade applications, develop laboratory scale systems (moving web) to verify their general validity, confirm the magnitude of benefits to be expected, and identify operating constraints and resolve problems not discernable at the bench scale.

7. Technical/Economic Assessment:

   Use the technical data from the laboratory verification work to improve upon the definition of design alternatives for water removal systems suitable for important paper and board grades and evaluate the mill-wide technical and economic impacts of these systems.

8. Define Best Systems and Applications:

   Develop and document the technical and economic data bases characterizing those water removal systems and applications having high payoff potential for the industry.

9. Pilot Verification (Optional):

Design, construct, and operate pilot-scale version(s) of the best system(s), capable of high-speed, continuous web operation, to provide a more complete and accurate evaluation of the technical and economic impact of improved water removal technology, thereby stimulating the timely development of commercial equipment.

Funding has been requested from the U.S. Department of Energy to expedite the accomplishment of the work proposed in this long-range plan. About four years would be required. At this time, we have very positive indications but no firm commitments from DOE.

RECENT/CURRENT WORK

Most of the recently completed research and work in progress to be discussed in this section is related to program elements 1 and 2 in the long-range plan (see Fig. 1), although preliminary consideration is also given to the engineering and system implications of the data. Work dealing with the drying performance and mechanisms of high-intensity drying is first presented. Then, the results of work on water removal and energy effectiveness in impulse drying are considered. Finally, some engineering and system aspects of the impulse drying data are discussed.

HIGH-INTENSITY DRYING: PERFORMANCE AND MECHANISMS

Most of the atmospheric high-intensity drying experiments discussed in previous status reports for this project can be classified into two regimes of mechanical pressure application: constant pressure drying, at levels below 5 psi*,

*Pressures up to approximately 40 psi were employed in thermal/vacuum drying experiments.

and dynamic pressure during drying (as in a heated press nip), at average levels of 220 to 1760 psi. The typical water removal rates in the latter regime were found to be two to three orders of magnitude larger than those in the former regime. The latter, very high rate, mode of operation has been termed impulse drying. Within each of these regimes, it is found that increases in mechanical pressure cause increases in drying rate.

In an attempt to gain further insight into the mechanisms of high-intensity drying and the transition to very high water removal rates typical of the impulse drying regime (where a significant liquid-phase component of water removal is thought to occur), a series of experiments at intermediate (and constant) mechanical pressures (5-300 psi) has been performed. The drying rates occurring during these tests are displayed in Fig. 2. It is evident that the importance of mechanical pressure increases at high mechanical pressures. This is contrary to the "conventional wisdom," which is based on experience in the operating range for conventional dryers (see Fig. 2).

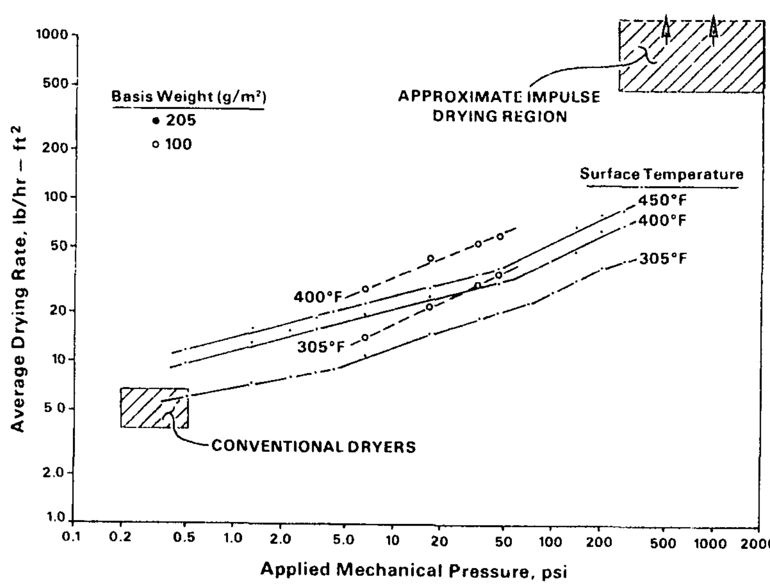

Figure 2. Average drying rate for unbleached softwood kraft handsheets with 60% initial moisture content, 6% final moisture content.

It should be noted that the pulp freeness (and thus the sheet flow resistance) has been found to have almost no effect on drying rate over most of the range of conditions (up to at least 50 psi) in Fig. 2. This is compatible with the simple two-zone model of high-intensity drying presented last year, in which heat transfer through a dry layer adjacent to the hot surface is considered to be the limiting step in the drying process. At very high mechanical pressures, however, the increased sheet compression would be expected to cause the flow resistance in the wet zone to take on more importance. An indirect consequence of this reasoning is that a gradually-increasing liquid-phase dewatering contribution (driven by increased vapor pressure in the sheet) would be expected to occur at the higher mechanical pressures. This contribution would help to explain the increasing slope of the curves in Fig. 2. A Ph.D. candidate, Joe Pounder, is extending the mathematical model to include the effects of flow resistance and liquid flow.

In spite of the factors just discussed, it appears from the data in Fig. 2 that the drying rates typical of true impulse drying (dynamic pressure) operation may exceed those in constant pressure drying, even at similar average pressure levels, temperatures, etc. If this is borne out, it would suggest that the pressure-time shape applied to the sheet during drying is an important "variable." Further exploration of this possibility is needed. Experiments by another Ph.D. candidate, Chris Devlin, at higher (but constant) pressures and temperatures may help to clarify the situation.

For many of the operating conditions corresponding to the data points in Fig. 2, the vapor pressure at the hot surface* and the surface temperature

*Note: Gage pressure, not absolute pressure.

response (used to compute the instantaneous heat flux and cumulative thermal energy transferred into the sheet) have been measured. Examples of the vapor pressure, heat flux, and energy transfer results are given in Fig. 3 through 5.

The vapor pressure is a significant quantity, since it is the driving force for vapor removal, and a major driving force for liquid flow, as well. The magnitude of the vapor pressure is governed by the vapor generation rate (essentially, the instantaneous drying rate, related to the instantaneous heat transfer rate to the sheet) and the flow resistance of the sheet to this vapor as it flows out to the surroundings. This statement is qualitatively confirmed by the similar shapes of the pressure and heat flux curves (Fig. 3 and 4). The peak pressures occurring at various freenesses and operating conditions are shown in Fig. 6. In general, the trends are physically reasonable; they also demonstrate that large driving forces for liquid-phase dewatering are developed at high temperature and mechanical pressure.

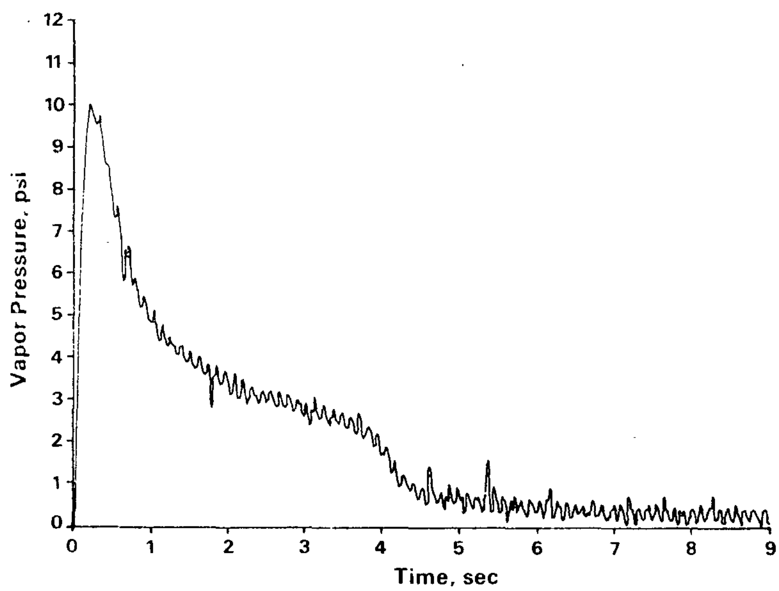

Figure 3. Vapor pressure at hot surface for unbleached softwood kraft handsheet, 205 g/m^2 basis weight, 60% initial moisture, 570 CSF, at 450°F surface temperature, 46.5 psi mechanical pressure.

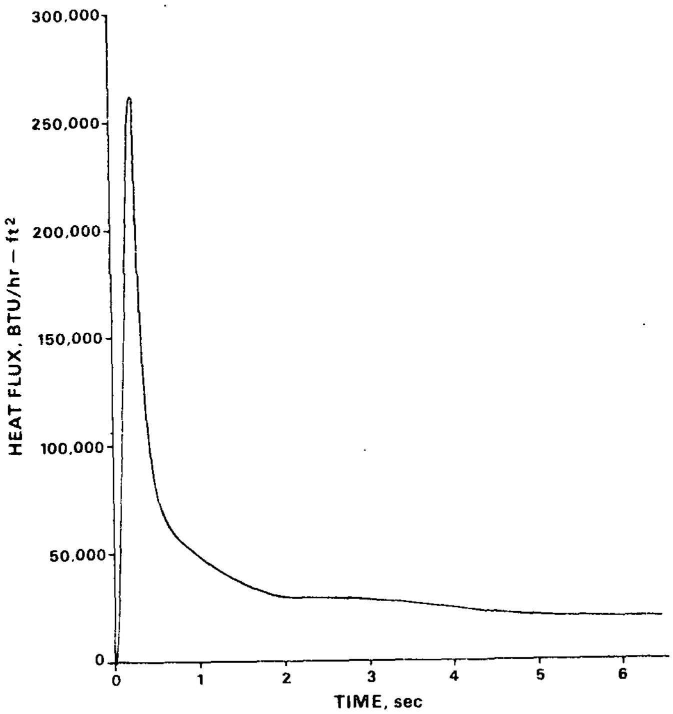

Figure 4. Heat flux into sheet. Same conditions as in Fig. 3.

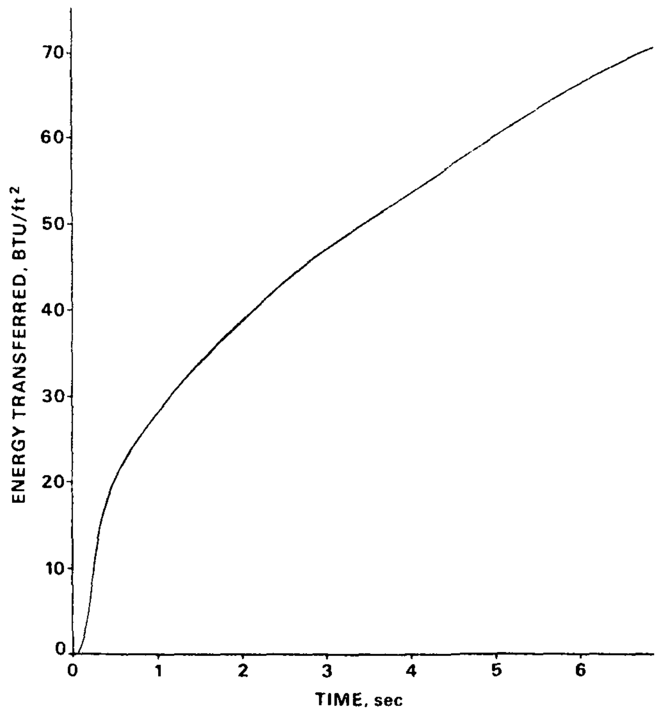

Figure 5. Energy transferred to sheet. Same conditions as Fig. 3.

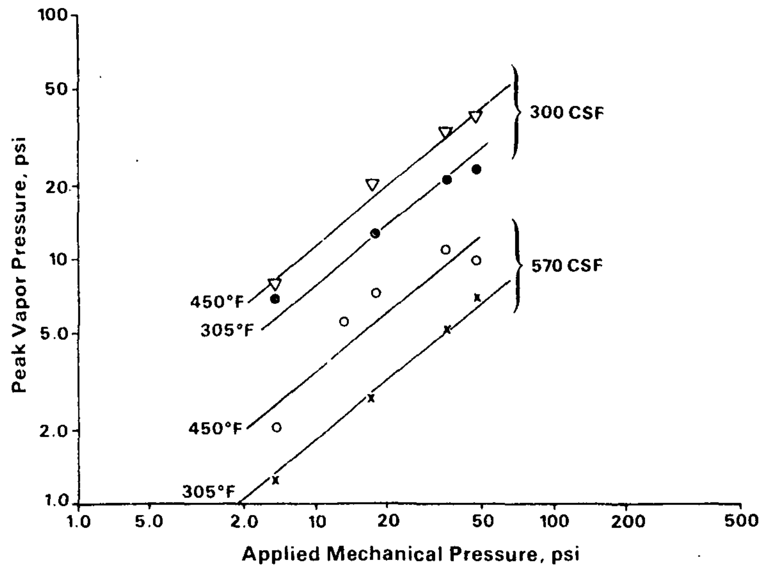

Figure 6. Peak vapor pressure at hot surface for unbleached softwood kraft handsheets, 205 g/m^2, 60% initial moisture content.

The energy transfer curve in Fig. 5 is the time integral of the heat flux from Fig. 4. The level attained near the end of the drying process (at about six seconds) is essentially that expected for a case where all water removal occurs by evaporation. It will be interesting to see whether the measured thermal energy transfer decreases when conditions typical of impulse drying are employed. This would signify the occurrence of liquid-phase dewatering.

WATER REMOVAL AND ENERGY EFFECTIVENESS IN IMPULSE DRYING

Previously reported impulse drying data from the heated roll apparatus were obtained using surface temperatures below 600°F. Recently, some additional water removal data have been obtained for 100 g/m^2 unbleached softwood kraft handsheets at 570 CSF, using temperatures in the 600-800°F range. These new data have been incorporated, along with previous data, into contour maps that facilitate the consideration of temperature-nip residence time tradeoffs. These maps are presented in Fig. 7 and 8, for two values of <u>average</u> nip mechanical

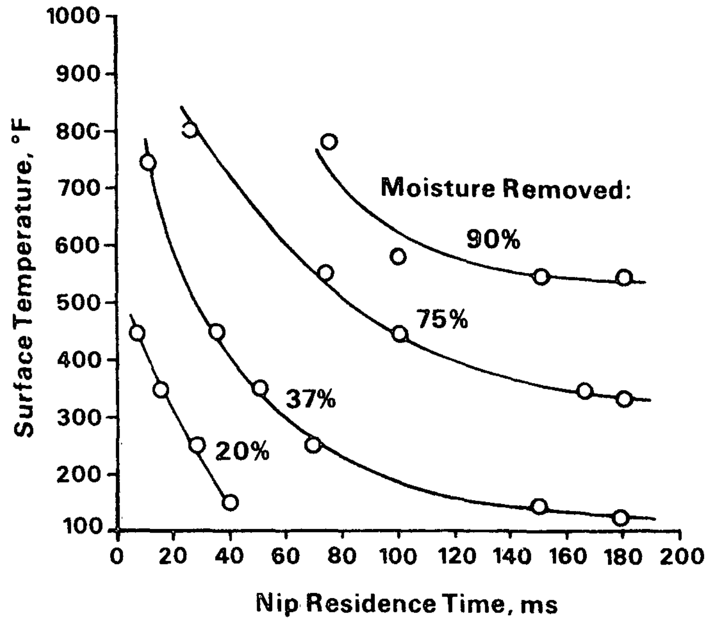

Figure 7. Relative moisture removed during impulse drying: 100 g/m^2 unbleached softwood kraft handsheets (570 CSF) at 58% initial moisture content, with 880 psi average mechanical pressure applied.

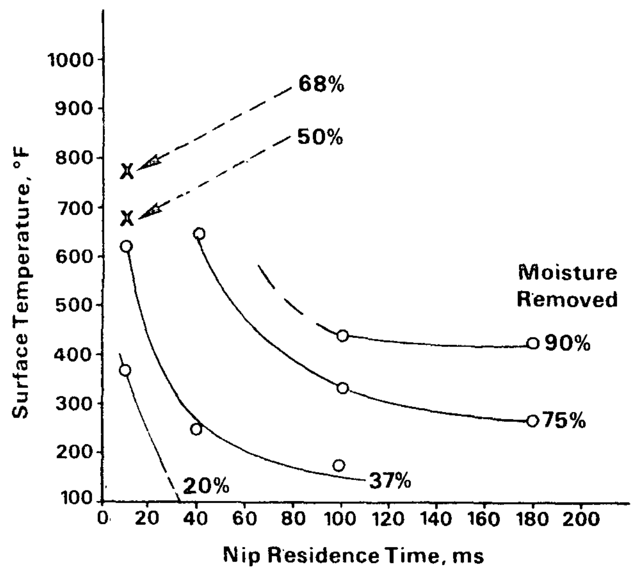

Figure 8. Relative moisture removed during impulse drying: same sheet specifications as in Fig. 7, with 1760 psi average mechanical pressure applied.

pressure (also an important influence on water removal). It is seen that, for very high pressure and temperature, the majority of the water in the sheet can be removed in times similar to those prevailing in an extended nip.

The "drying rates" at the extreme conditions are very large. For example, the point in Fig. 8 corresponding to 75% water removed at 40 ms (at 650°F, 1760 psi) is equivalent to a drying rate of approximately 3800 lb/hr ft^2. It is certainly likely that an appreciable component of the water removal must be in the liquid phase, for such high rates to occur. If this is true, the thermal energy needed for drying would be reduced accordingly. In order to determine the approximate amounts of liquid dewatering which do occur, some tests have been performed to determine the amount of loss of a tracer (sodium fluorescein), considered to be transported from the sheet by liquid water. Results of these tests are given in Fig. 9 and 10 for nip residence times of 10 and 25 ms, respectively. The data are very encouraging in that they show a tendency for both the absolute amount and the proportion of liquid removed to increase as the total water removal increases (i.e., at higher temperature and longer time). It must be acknowledged that some uncertainties exist in translating the dye loss amounts into water removal figures. Two potential sources of uncertainty (which tend to compensate) are the possibility of nonuniform dye concentration (at the fiber level) in the sheet before testing and dilution of dyed water in the cooler portion of the sheet by condensation. While these possibilities are under investigation, neither is presently thought to be of extreme importance.

It is worth noting that one test condition was explored using 100 g/m^2 handsheets made from once-dried bleached kraft pulp at 720 CSF. At 550°F, 880 psi average pressure and 25-30 ms nip residence time, 80% of the initial moisture (the initial moisture ratio was approximately 1.5) was removed with

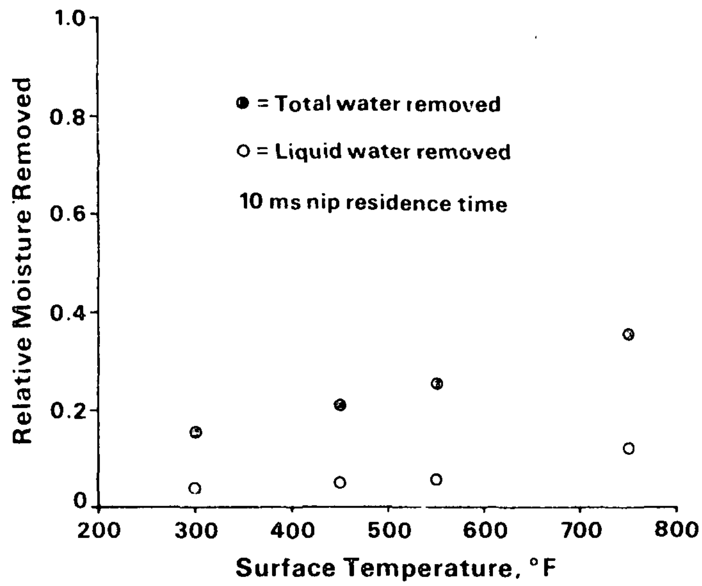

Figure 9. Total relative moisture removed and relative moisture removed as liquid: same sheet specifications as in Fig. 7, with 880 psi average applied mechanical pressure applied and 10 ms nip residence time.

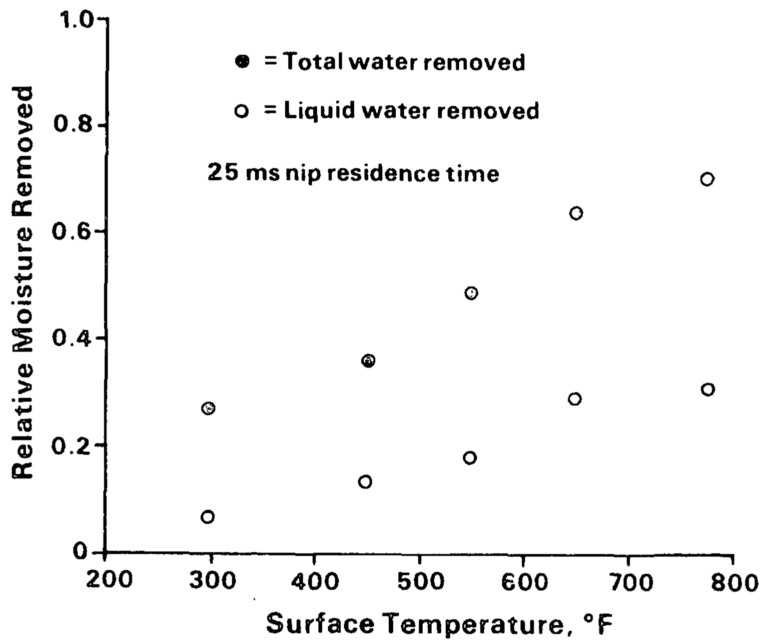

Figure 10. Total relative moisture removed and relative moisture removed as liquid: same conditions as in Fig. 9, except 25 ms nip residence time.

about two-thirds of this occurring in the liquid state! Interestingly, the amount of vapor-phase water removal was about the same as occurred from the sheets upon which Fig. 10 is based, at the same operating condition.

ENGINEERING AND SYSTEM ASPECTS OF IMPULSE DRYING

It is of interest to consider (on a preliminary basis) some of the engineering implications and questions suggested by the water removal maps (for 100 g/m^2 sheets) shown in Fig. 7 and 8. In general, it appears that nip residence times typical of extended nip presses (e.g., 50 ms) would be needed to produce interesting amounts of water removal (e.g., on the order of 75% of the initial moisture present) from these sheets. It is clear, however, that high average nip pressures and high surface temperatures would also be required. For example, according to Fig. 7 and 8, surface temperature/average pressure combinations of about 660°F/880 psi or 540°F/1760 psi would be needed to achieve 75% water removal in a nip residence time of 50 ms.

The high temperature levels indicated for impulse drying suggest that practical alternatives to steam heating will be necessary. Some options that should be considered include: direct heating of the dryer surface with combustion products, indirect heating (e.g., circulating of heated liquids through the shell), and electrical heating. The various options will not only have impacts on the operating cost, but also on the associated equipment size (due to heat flux limitations, etc.).

The relatively severe operating conditions indicated for impulse drying also suggest that mechanical design considerations will play a major role in defining the practical limits of impulse drying, as they do in defining the optimum configuration in Yankee dryers. In particular, the mechanical effects of high pressures and temperature levels and large temperature gradients in the nip region will require careful analysis. On a different scale, it should be noted that as nip pressure levels and residence times are increased, the structure required for the dryer will become considerably more massive. There is no apparent reason why the economic optimum size will be the same for impulse drying as it is for wet pressing with extended nip technology, but this will need to be explored.

The energy implications of the liquid removal data in Fig. 9 and 10 are very significant. For example, at the maximum water removal conditions shown in Fig. 10 (having a total of 70% of the initial sheet moisture removed, with 30% of the initial moisture removed as liquid), only about 600 Btu/lb fiber would be needed for "drying." In contrast, it is estimated that about 1500 Btu/lb fiber (2½ times that of the impulse dryer case) would be used in a conventional dryer to accomplish the same amount of dewatering. It should be noted that these estimates assume the conventional dryer uses about 50% more energy per unit of evaporation than does the impulse dryer, reflecting the greater losses expected in a conventional system as a result of the much larger size and the indirect heating method.

In contrast to the reduced quantity of energy needed with impulse drying, it should be observed that the quality (value) of the energy required to provide the high temperature levels associated with impulse drying may exceed that used in conventional dryers. It is obvious, therefore, that the overall energy and cost implications of impulse drying will need a much more complete evaluation after more extensive performance data are available.

TECHNICAL EVALUATION OF ADVANCED WATER REMOVAL PROCESSES

Advanced water removal processes such as impulse drying or thermal/vacuum drying may be better suited, technically and economically, for some paper grades than for others. To provide the data needed to more completely characterize the performance of these drying systems and for determining the most attractive applications, bench-scale tests covering a representative range of paper grades, furnishes, and operating conditions will be undertaken. A significantly expanded data base, covering drying rates, energy consumption, paper properties, etc., will be developed in this test program.

Unfortunately, it is impractical to experiment with all combinations of fiber furnish, refining level, basis weight, etc., over a broad range of operating conditions. Therefore, a limited selection of these combinations, representative of certain important paper and board grades, has been tentatively selected for use in evaluating the advanced processes. Based on production figures the grades listed in Table I seem reasonable for this study. A preliminary

TABLE I

CANDIDATE GRADES FOR CHARACTERIZATION TESTS

Paper	Percent of Total U.S. Production[a]	Board	Percent of Total U.S. Production[a]
1. Newsprint	7.7	4. Linerboard	23.1
2. Uncoated printing or writing paper	13.2	5. Corrugating medium	7.3
3. Tissue	7.2	6. Recycled Paperboard	11.6

[a]Combined paper and board production. Overall, grades listed represent about 70% of total U.S. paper and board production.

3. The characterization test results will be utilized in defining and evaluating the engineering aspects of implementation. In particular, the heat input time/surface temperature/mechanical pressure combinations required to achieve relevant dryness and paper properties targets will be used to define appropriate system configurations and heat source alternatives. System and engineering analyses of the alternatives will be initiated in order to guide the selection of the most promising water removal system concepts.

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3527

MEASUREMENT OF FIBER PROPERTIES AND

FIBER-TO-FIBER BONDING

February 10, 1984

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

Date:	Feb. 16, 1984
Budget:	$85,000
Period Ends:	6/30/84
Project No.:	3527

PROJECT TITLE: MEASUREMENT OF FIBER PROPERTIES AND FIBER-TO-FIBER BONDING

PROJECT STAFF: K. W. Hardacker/G. A. Baum

PROGRAM GOAL: Bring new attributes to wood-based products.

PROJECT OBJECTIVE:

The ultimate project objective is to define steps for making a paper of superior strength and with superior performance at high humidities. The immediate objective is to develop instrumentation to measure fiber mechanical properties in order to better understand the action of water in degrading fiber strength, stiffness, and fiber-fiber bonding.

PROJECT RATIONALE, PREVIOUS ACTIVITY, and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS LAST PERIOD: (March 1983 - September 1983)

(1) A review of the literature concerned with equipment or instrumentation to measure fiber properties was conducted.

(2) An ad hoc committee (G. Baum, J. Becher, K. Hardacker, T. McDonough, and R. Stratton) was formed to determine (among other things) which fiber parameters would be desirable to measure in a study of bond strength enhancement, and which of those parameters might be measureable. Together with the literature review, it was decided that fiber axial properties (modulus, strength, toughness) and transverse properties (load to lumen collapse, cell wall modulus, cell wall shear modulus) were desirable and obtainable, in addition to fiber-fiber bond strength. All of these should be measureable at various moisture content levels.

(3) An instrument suitable for making such measurements, with precision superior to other existing equipment, is in the design stage.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

(1) Design of the new instrument is underway, with several elements complete, and others in fabrication. The details are presented in the attached report.

PROJECT TITLE: Measurement of Fiber Properties and Fiber-to-Fiber Bonding	Date: 4/19/83
PROJECT STAFF: G. A. Baum	Budget: $85,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use.	Period Ends: 6/30/84
PROGRAM AREA: Moisture Tolerant, Superior Strength Paper and Board.	Project No.: 3527
	Approved by VP-R:

PROGRAM GOAL: Bring new attributes to wood-based products.

PROJECT OBJECTIVE:

The ultimate project objective is to define steps for making a paper of superior strength and with superior performance at high humidities. The immediate objective is to better understand the action of water in degrading fiber strength, stiffness, and fiber-fiber bonding.

PROJECT RATIONALE:

At present, commercial papers do not attain strength levels that realize the full potential of existing wood fibers. Most paper mechanical properties are markedly degraded with increasing paper moisture content. We need to better understand the nature of these changes in fiber properties and fiber-to-fiber bonding with increasing moisture content, if we are eventually to improve the moisture tolerance of paper.

RESULTS TO DATE:

There has been limited activity on this project to date. A literature search has been conducted. Ultrasonic techniques have been used to measure the in-plane and out-of-plane elastic constants of paper up to moisture contents of 60%. Above about 40% moisture, the water in the sheet dominates the measurement.

SHORT TERM GOALS:

This effort represents a start on one of our expansion projects. The short term goals are to evaluate the capabilities of existing equipment to make measurements of fiber properties as a function of moisture content, and to develop new instruments and techniques, as needed, to measure fiber properties and fiber-to-fiber bond strength <u>vs</u> moisture content.

PLANNED ACTIVITY FOR THE PERIOD:

We plan to (1) review existing techniques for making the desired measurements, (2) to adapt the best of these for use in measuring properties as functions of moisture content (to 20%), and (3) to develop new equipment or techniques, as needed. Fiber properties of interest include axial stiffness and strength, transverse strength, and transverse shear stiffness and strength.

POTENTIAL FUTURE ACTIVITIES:

Future activities are documented in the long-range project plans.

Status Report

MEASUREMENT OF FIBER PROPERTIES AND FIBER-FIBER BONDING

Project 3527

One facet of the development of moisture tolerant, superior strength paper is the determination of the effects of moisture on the individual fibers and on the bonds between the fibers. Measurements of the following properties are indicated:

1. Fiber axial tensile load/elongation characteristic
   - Breaking stress
   - Breaking strain
   - Work to rupture
   - Initial modulus
2. Tensile characteristics of various bonded-fiber-pair configurations.
3. Fiber transverse tensile load/deformation characteristics.
4. Fiber (and crossed fibers) transverse compression load/deformation characteristics.
5. Fiber cell wall shear modulus.

A literature survey was made to determine how other investigators had made these measurements. No single method appeared well suited to making all the desired measurements. In fact, the Institute's existing Fiber Load Elongation Recorder, with suitable fixtures, could be used for measurements 1-4 except for marginal sensitivity for the transverse measurements.

Rather than try to upgrade the Fiber Load Elongation Recorder, it was decided to design and construct a versatile new instrument with adequate range and sensitivity.

Design of this new instrument has progressed to the stage of detailing the individual components needed. Scale drawings are shown in Figs. 1 and 2. In essence, an electronic weighing cell, A, is suspended beneath a mounting plate, B, by means of four flexure springs, C. A dc servo motor, D, turns a differential screw, E, pulling or pushing the weighing cell to apply a tensile or compression load to a specimen mounted between the clamps, F. The right hand clamp may be positioned along the test axis by the compound microscope focusing mechanism, G, and be locked in place by the clamp, H. Specimen extension or compression is measured between this fixed clamp and the opposing, movable clamp. A capacitive displacement transducer, I, supported by the pillar, J, senses the position of the movable clamp.

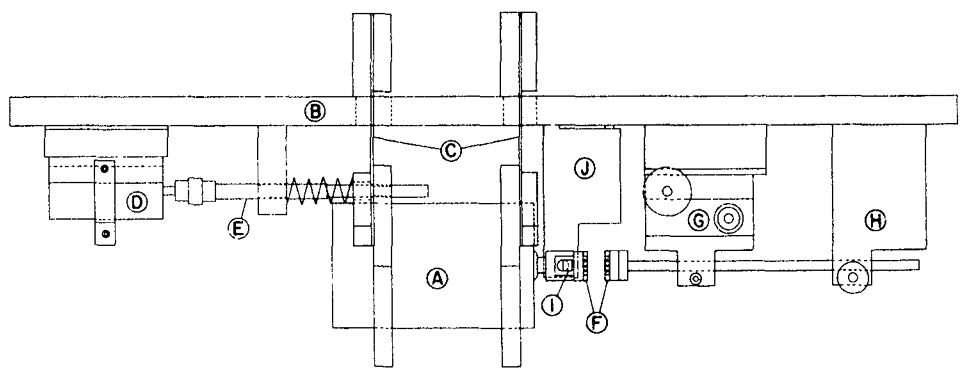

Figure 1. Side view of the Fiber Load Elongation Recorder, Model II. Scale: 1 in = 5 in. A - electronic weighing cell, B - mounting plate, C - flexure springs, D - dc servo motor, E - differential screw, F - clamps, G - microscope focusing mechanism, H - clamp, I - transducer, and J - pillar.

The signal for driving the dc motor will be derived by comparing the signal from the load or elongation sensor with a linear ramp reference voltage. Thus, testing may be done either at constant rate of loading or constant rate of elongation. Use of other reference waveforms will also be possible, if desired; e.g., logarithmic rate change, hold at constant load or elongation,

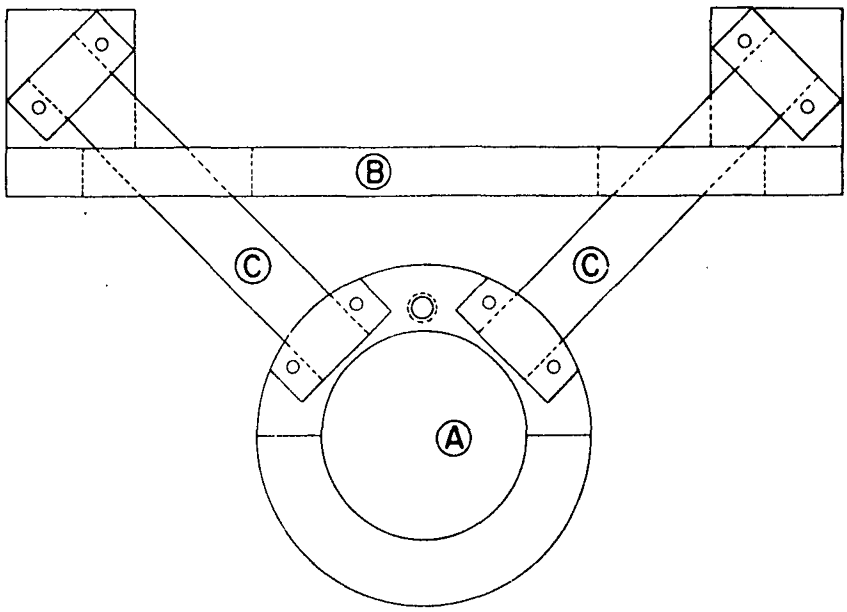

Figure 2. End view of the mounting structure for the load cell of the Fiber Load Elongation Recorder, Model II. A - electronic weighing cell, B - mounting plate, C - flexure springs.

sine wave cycling, rate proportional to measured work input, etc. This ramp generator has been designed but not yet constructed. Some parameters are listed in Table I.

TABLE I

MEASUREMENT RANGES

	Range	Sensitivity
Load cell I	50 grams	1 milligram
Load cell II	400 grams	5 milligrams
Elongation sensor I	0.05 mm	0.05 μm
Elongation sensor II	0.25 mm	0.25 μm
Time to full scale load elongation	2 sec to 400 sec	

The electrical drive circuit for the load cells has been constructed; preliminary tests show it to be operating satisfactorily. Also, the necessary modifications have been made to the purchased readout circuitry for the elongation transducers to permit automatically stopping the specimen loading system when the limits of the linear response of the measuring system are reached.

A suitable stereoscopic microscope has been selected and ordered to permit viewing and photographing the specimens during the tests.

Fiber and bond tests are to be conducted at various moisture contents. This necessitates immersing the specimens in various relative humidity atmospheres by (a) placing the apparatus in suitably conditioned rooms, (b) conditioning the interior of a box containing the apparatus, or (c) bathing the specimen in a gentle stream of conditioned air.

After considerable thought, it was decided to start work with the apparatus in a 50% RH, 73°F room and to vary the specimen moisture contents, at 73°F, by passing air conditioned to the other relative humidities over the specimens. This custom-conditioned air will be produced by mixing dry air from a tank of compressed, dry air with moisture-saturated air produced with a small bubble-type saturator. The air flow rates required are low enough and the moisture equilibration rates of single fibers are fast enough to make this a practical, relatively inexpensive process, while also providing maximum ease of access to the test area.

If it is desired at some later time to test at other temperatures, it would probably be best to supply larger quantities of conditioned air to a box containing the apparatus. This air might best be provided by a commercial, mechanically refrigerated, air handling unit. These tend to be quite large and expensive.

K. W. Hardacker
2/10/84

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3526

FUNDAMENTALS OF INTERNAL STRENGTH ENHANCEMENT

Improved Bonding via Chemical Additives

Fundamentals of Bonding in Conventional Pulps

February 10, 1984

Date:	Feb. 10, 1984
Budget:	$245,000
Period Ends:	6/30/84
Project No.:	3526

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

PROJECT TITLE: FUNDAMENTALS OF INTERNAL STRENGTH ENHANCEMENT
Improved Bonding via Chemical Additives
Fundamentals of Bonding in Conventional Pulps

PROJECT STAFF: R. A. Stratton/J. J. Becher

PROGRAM GOAL: To bring new attributes to wood-based products

PROJECT OBJECTIVE:

To improve internal strength and moisture tolerance in paper and paperboard. The short terms goals are to establish those parameters fundamental to inter-fiber and intra-fiber bonding in conventional and ultra high yield pulps and to control these parameters, if possible, by chemical or mechanical treatments.

PROJECT RATIONALE, PREVIOUS ACTIVITY, and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Program Form.

SUMMARY OF RESULTS LAST PERIOD: (March 1983 - September 1983)

(1) An ad hoc committee was formed in June to establish a reasonable research plan to reach the short term goals and to review progress. This group includes G. A. Baum, J. J. Becher, K. W. Hardacker, T. J. McDonough and R. A. Stratton.

Because suitable instrumentation to measure desired fiber properties is not yet available, activity thus far has centered on improved bonding via chemical additives and the fundamentals of bonding in conventional pulps.

(2) The use of chemical agents to enhance bonding was discussed in the last report. Here, the focus to date has been on additives that interact with the fiber surfaces via electrostatic attraction. Improvements in both wet strength and dry strength were induced in a very pure (alpha cellulose) pulp and in a 49% yield softwood unbleached kraft pulp.

(3) The fundamental fiber/fiber bond is of primary concern. Activity during the first three months of this project focused on developing techniques to determine the locus of failure of the bond. In particular we are trying to establish whether "bond" failure occurs in the bonded area between fibers (as we usually assume) or in one of the fiber cell walls. Exploratory work using optical and scanning electron microscopy was described in the last report.

(4) Another area deals with improving our understanding of the bonding mechanisms in ultra high yield pulps. Studies of the mechanisms and of methods to enhance bond strength will be initiated during the next six months.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

(1) Concerning the use of chemical additives, the moist and wet tensile factors were corrected to a constant sheet density. As described in the attached Section 1, this did slightly reduce these factors, but the original conclusions remained the same. A study to determine whether the treated papers absorbed less moisture revealed that treated and untreated sheets had about the same moisture content at a given RH.

(2) Certain of the treated papers showed a lack of sizing, but it was determined that sizing agents could be used without degrading the benefits from the strength additives, as discussed in Section 1.

(3) The effect of fines in conjunction with strong additives were studied. In general, whole pulp handsheets were stronger than sheets from classified pulps. It is believed that the strength additives are preferentially retained by fines and thus have a lesser effect in the case of the classified pulps (Section 1).

(4) Concerning fiber bonding studies, work has expanded to include locations of bond failure in unrefined EW and LW fiber systems and refined (300 CSF) fibers (Section 2 attached). For either the EW or LW fiber systems bond failure can occur either in the cell wall or between fibers. The governing factors are not yet understood. The mode of failure with the refined fibers is more difficult to establish because of the altered surfaces due to refining. This work is continuing.

(5) The strength of fiber-fiber bonds have been measured for (1) bonds wet pressed and air dried and (2) wet pressed and oven dried but maintaining a low pressure. Refined fibers, as anticipated, produce stronger bonds. This work is described in the attached Section 2.

PROJECT TITLE: Fundamentals of Internal Strength Enhancement	Date: 4/19/83
PROJECT STAFF: R. Mikhail/R. A. Stratton	Budget: $245,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use.	Period Ends: 6/30/84
PROGRAM AREA: Moisture tolerant, superior strength paper and board.	Project No.: 3526
PROGRAM GOAL: To bring new attributes to wood-based products	Approved by VP-R:

PROJECT OBJECTIVE:

To improve internal strength and moisture tolerance in paper and paperboard.

PROJECT RATIONALE:

Major limitations of paper and board for many uses are low internal bond strength and poor moisture tolerance. Improved internal strength and enhanced moisture resistance would allow a number of present grades to be produced using less fiber and would also allow new end uses to be developed.

Size pressing is one way currently used to enhance internal strength. If this operation could be eliminated, or substantially changed to improve paper machine runnability, paper machine productivity could be also significantly improved.

RESULTS TO DATE:

A literature survey and state-of-the-art report have been prepared.

SHORT TERM GOALS:

The short terms goals are to establish those parameters fundamental to inter-fiber and intra-fiber bonding in conventional and ultra high yield pulps and to control these parameters, if possible, by chemical or mechanical treatments.

PLANNED ACTIVITY FOR THE PERIOD:

This project is complementary to two expansion projects: one concerned with moisture tolerant products and the other high yield pulps. In addition, another project in the FY 83-84 budget is concerned with the development of instruments which will be eventually used in this project (and the expansion projects.)

The following activities are planned for this fiscal year.
(1) A program will be initiated to identify those parameters critical to bonding which can be controlled by chemical or mechanical treatments to the fiber.
(2) Several promising methods for improving bonding in conventional pulp furnishes, that were mentioned in the literature, will be evaluated in enough detail to determine optimum conditions and as starting points for novel treatments.
(3) A survey of the literature together with an assessment of current work (through personal contacts) will be undertaken to identify those parameters fundamental to bonding in ultra high yield pulps. It is anticipated that some or all of these parameters will be different from those found in (1) above.

It is likely that all three areas will be continued in the following fiscal year, FY 84-85.

SECTION 1

FUNDAMENTALS OF INTERNAL STRENGTH ENHANCEMENT

Improved Bonding via Chemical Additives

Project 3526

INTRODUCTION

Results reported at the previous meeting indicated that several mixtures of polymeric materials produced superior strength properties when added to an unclassified high alpha pulp and to a classified unbleached kraft from southern pine. The strength properties were of a higher level than those obtained through addition of the individual components suggesting a synergism presumably due to ionic or covalent bonding. Some of the more interesting of these combinations were carboxy methyl cellulose (CMC) and polyamide polyamine epichlorohydrin (PAE), added separately, and 1:1 blends of polyvinyl alcohol (PVA) and PAE when combined with polyacrylic acid (PAA). Employing the aforementioned combinations under optimum or near optimum conditions provided moist tensile factors in excess of 2.0 and wet tensile factors in excess of 17.0 (treated/untreated). Polyvinyl alcohol and trimethylol melamine (TMM) combinations were found to be somewhat less effective.

RESEARCH RESULTS

Several units of work were undertaken on the basis of questions and comments made by the committee. One of these involved correcting the moist and wet tensile factors to a constant sheet density, i.e., to that of the untreated controls. This correction is reasonable since the densities of the treated (stronger) papers were higher than those of the untreated controls. The uncorrected and corrected values for the CMC/PAE combinations are listed in Table I and selected results are presented in Fig. 1 and 2. It is evident from these results that correcting to a constant density tended to reduce moist and wet tensile factors but the original conclusions remain the same, i.e., selected treatments provided a distinct advantage over the controls.

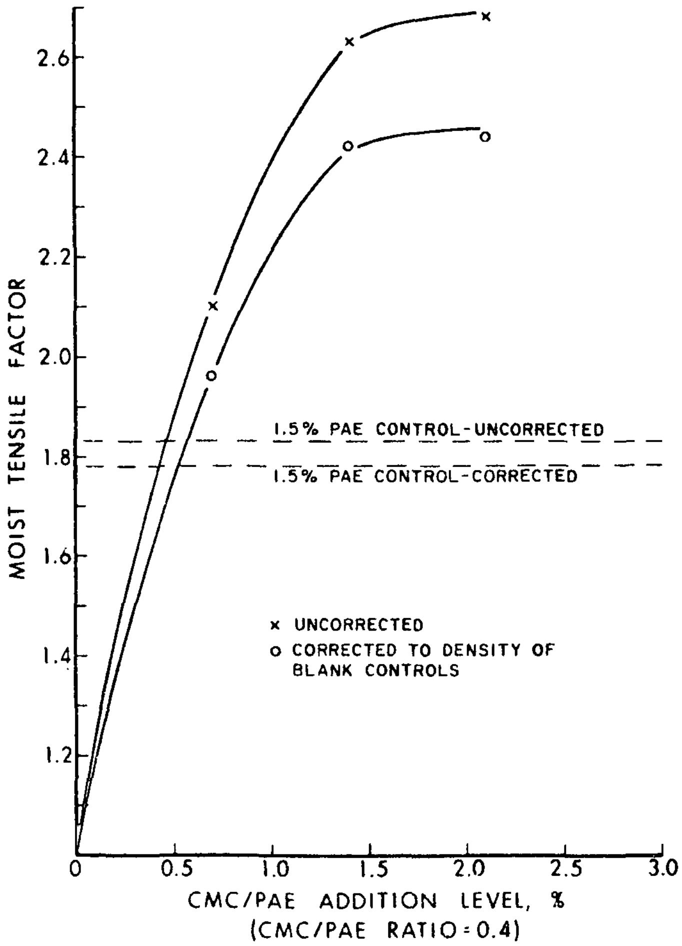

Figure 1. The effect of CMC/PAE addition level on moist tensile factor (classified unbl. kraft - 48.8 yield, Kappa no. 33.7).

A second segment of work involved measuring the moisture content of paper equilibrated to relative humidities ranging from 50-93%. The purpose of this work was to determine if the treated papers absorbed less moisture and were thereby capable of providing higher moist tensile factors. The results which

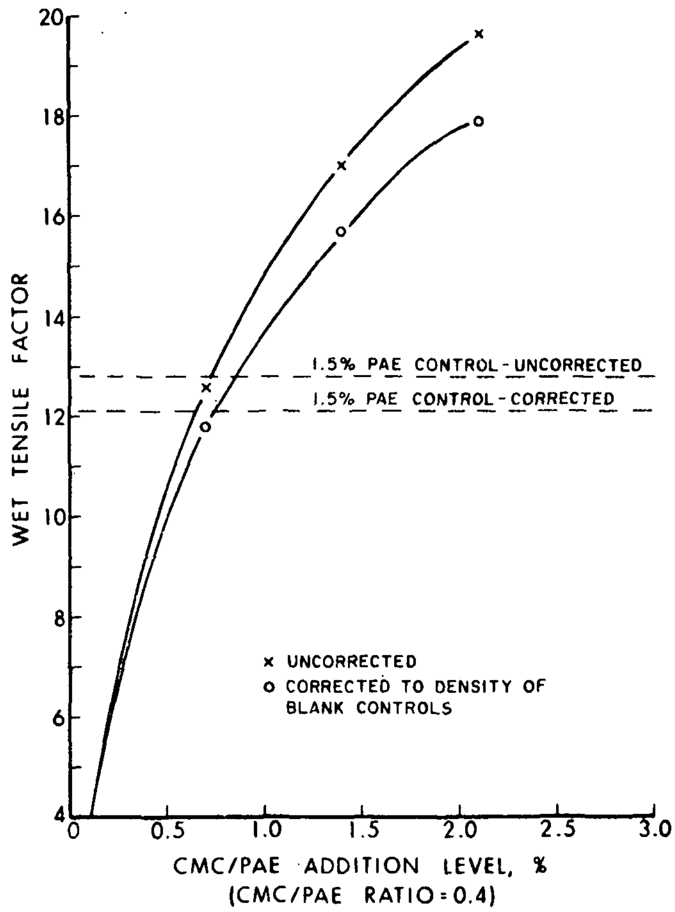

Figure 2. The effect of CMC/PAE addition level on wet tensile factor (classified unbl. kraft - 48.8% yield, Kappa no. 33.7).

TABLE I

TENSILE PROPERTIES CORRECTED FOR DIFFERENCES IN SHEET DENSITY

(Classified Unbleached Kraft Pulp - Cook #1, 48.8% Yield; Kappa No. 33.7)

Set No.	Additives, % Based on Fiber	CMC/PAE ratio	Basis Weight, g/m²	Apparent Density, g/cc	Dry Breaking Length, Km Uncor	Dry Breaking Length, Km Cor[a]	Moist Breaking Length, Km Uncor	Moist Breaking Length, Km Cor[a]	Moist Tensile Factor Uncor	Moist Tensile Factor Cor[a]	Wet Breaking Length, Km Uncor	Wet Breaking Length, Km Cor[a]	Wet Tensile Factor Uncor	Wet Tensile Factor Cor[a]
1	Blank Control	-	63.1	0.390	3.22	3.22	1.89	1.89	1.0	1.0	0.108	0.108	1.0	1.0
2	Control - PAE,1.5	-	64.8	0.400	5.08	4.95	3.46	3.37	1.83	1.78	1.38	1.38	12.77	12.12
3	Control - CMC,0.4	-	61.7	0.396	3.31	3.26	1.86	1.83	0.98	0.97	0.099	0.097	0.92	0.90
4	PAE,1.0; CMC,0.4	0.4	62.9	0.423	7.18	6.60	4.98	4.58	2.63	2.42	1.84	1.69	17.04	15.65
5	PAE,1.5; CMC,0.6	0.4	63.0	0.429	7.43	6.76	5.07	4.61	2.68	2.44	2.12	1.93	19.63	17.87
6	PAE,0.5; CMC,0.2	0.4	64.0	0.418	6.33	5.90	3.98	3.71	2.10	1.96	1.36	1.27	12.60	11.76
7	PAE,1.0; CMC,0.25	0.25	63.2	0.416	6.37	5.98	4.52	4.24	2.39	2.24	1.74	1.63	16.11	15.09

[a]Corrected to the density of the blank control.

are presented in Figs. 3-5 show that the treated papers had about the same moisture content as the untreated papers at a given relative humidity although some differences are indicated in Figs. 4 and 5. However, in examining these differences, the treated papers tend to have higher moisture contents than the controls. Hence, differences in performance cannot be attributed to this factor.

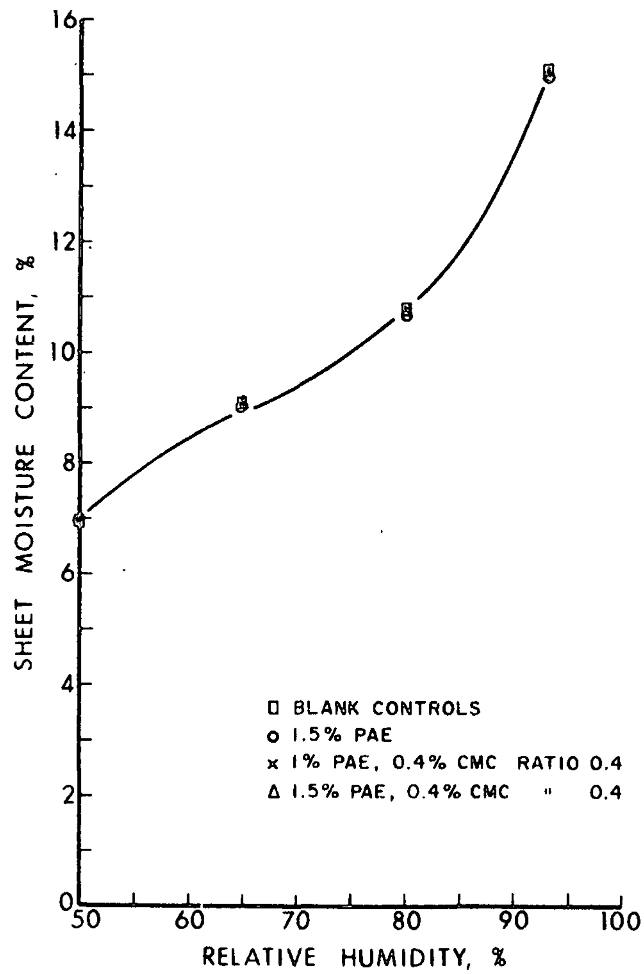

Figure 3. The effect of relative humidity on sheet moisture content (classified unbl. kraft - 48.8% yield, Kappa no. 33.7; CMC/PAE combinations).

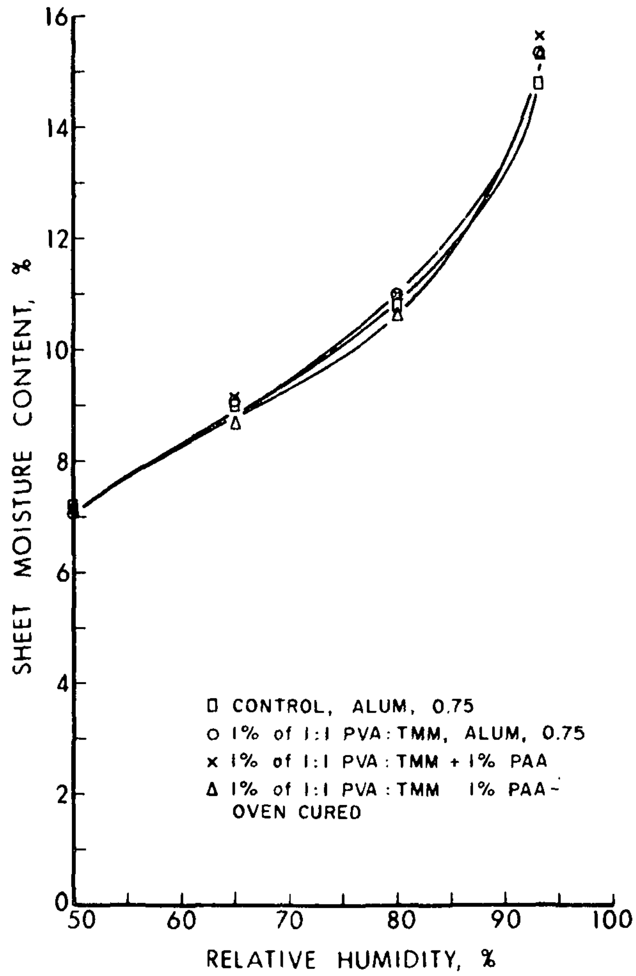

Figure 4. The effect of relative humidity on sheet moisture content (classified unbl. kraft - 48.8% yield, Kappa no. 33.7; PVA/TMM combinations).

While information in the literature (1) indicates that the optimum CMC/PAE ratio for strength enhancement should be approximately 0.4, this matter was pursued with our classified softwood unbleached kraft pulp. Since the initial supply of pulp was expended in studies completed to this point in the program, a second supply was prepared under nominally similar conditions. The second batch had a yield of 47.2% and a Kappa no. of 34.3 compared to a yield and Kappa no. of 48.8% and 33.7, respectively, for the original sample. It should be noted

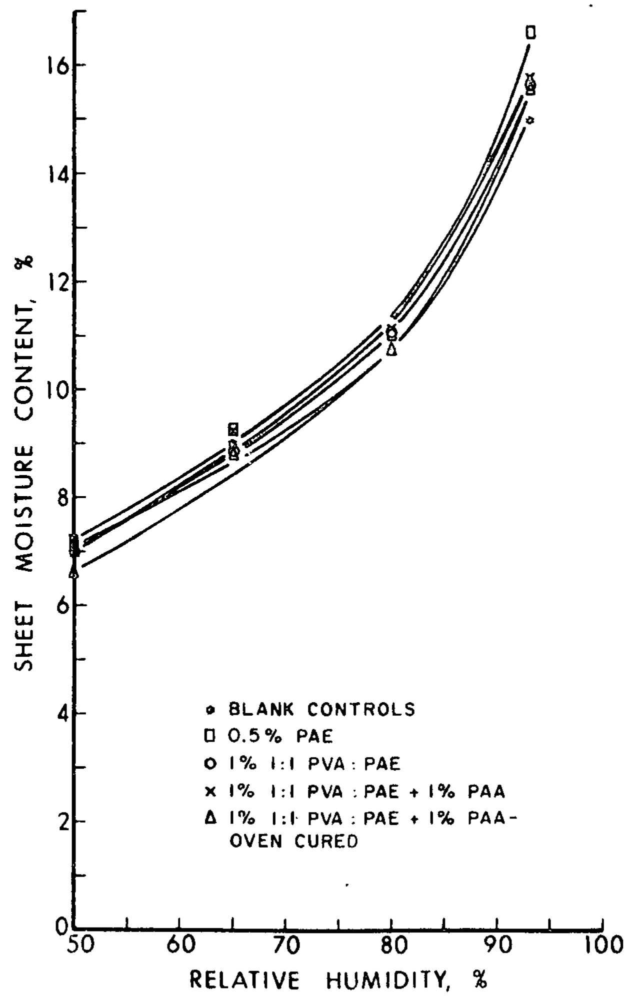

Figure 5. The effect of relative humidity on sheet moisture content (classified unbl. kraft - 48.8% yield, Kappa no. 33.7; PVA/PAE combinations).

that the second pulp was somewhat weaker than the first and this is believed to affect the response to additives and the resulting moist and wet tensile factors. The effect of CMC/PAE ratio at a total addition of 1% was subsequently examined and the results are recorded in Table II and Fig. 6 and 7. While the results show differing responses, there is very little, if any, significant difference between successive points in either curve considering the expanded scale in

Fig. 6 and the statistics involved. Espy (1) suggests that PAE predominates the retention at CMC/PAE ratios up to approximately 0.4. At high CMC/PAE ratios, the combination becomes anionic and is no longer adsorbed. The dependence of strength properties upon CMC/PAE ratio is related to the D.S. of the CMC, the charge density of the PAE resin and it is said to diminish in hard water as was used in this study.

It may be well at this point to consider the cost effectiveness of the CMC/PAE system. If one considers the results in Table II, the most effective CMC/PAE combinations (sets 10 and 11) would cost roughly $34 or $35/ton compared to $37-$38/ton for 1% of PAE (Set 9). Thus, the CMC/PAE combinations provided advantages in tensile properties at somewhat lower cost.

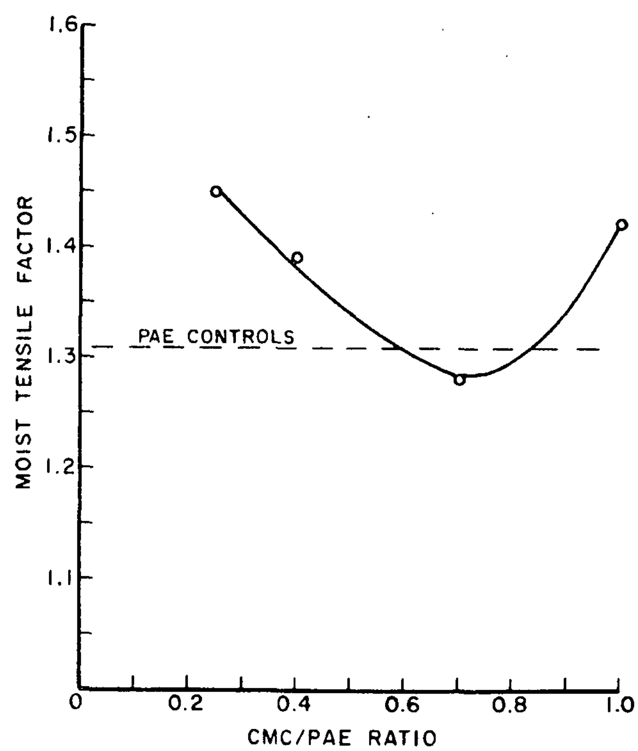

Figure 6. The effect of CMC/PAE ratio on moist tensile factor (classified unbl. kraft - 47.2% yield, Kappa no. 34.3; 1% addition).

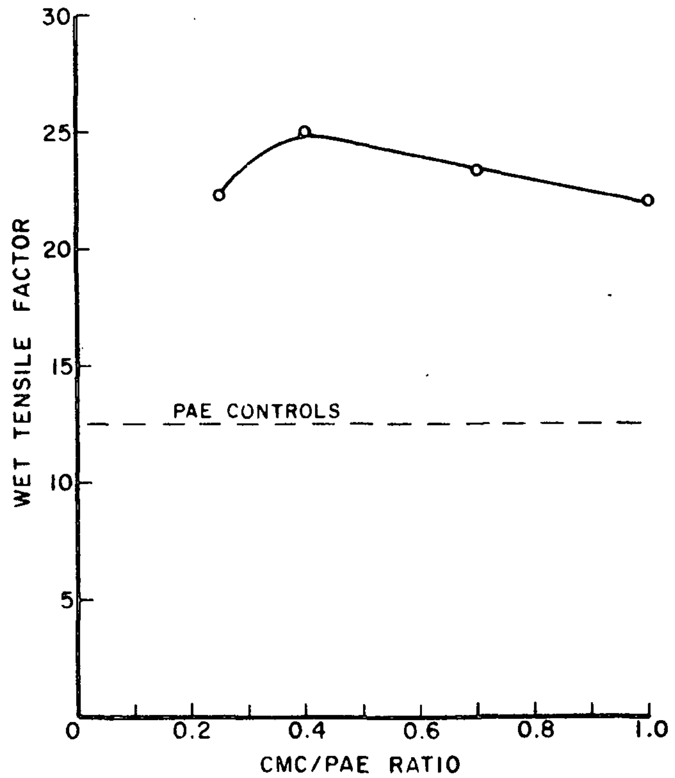

Figure 7. The effect of CMC/PAE ratio on wet tensile factor (classified unbl. kraft - 47.2% yield, Kappa no. 34.3; 1% addition).

TABLE II

THE EFFECT OF CMC/PAE RATIO ON STRENGTH PROPERTIES

(Classified Unbleached Kraft - Cook #2; 47.2% Yield; Kappa No. 34.3)

Set No.	Additives, % Based on Fiber	CMC/PAE ratio	Basis Wt., g/m^2	Thick-ness, μm	Apparent Density, g/cc	Dry Strength Properties Breaking Length, Km		Dry Strength Properties Et[a], kg/cm		Moist Strength Properties Breaking Length, Km		Moist Strength Properties Et[a], kg/cm		Moist Tensile Factor	Wet Breaking Length, Km		Wet Tensile Factor	Sizing (Water Drop Test) Sec.
							SD		SD		SD		SD			SD		
8	Blank Controls	-	60.9	158	0.386	2.90	0.165	209	17.4	1.34	0.100	96.5	11.0	1.0	0.06	0.006	1.0	Instantaneous
9	Controls, PAE,1.0	-	63.2	163	0.388	4.47	0.358	273	12.3	1.76	0.189	104	13.9	1.31	0.75	0.034	12.5	Instantaneous
10	PAE,0.8; CMC,0.2	0.25	68.4	169	0.406	6.08	0.313	368	8.6	1.94	0.066	109	3.20	1.45	1.34	0.075	22.3	Instantaneous
11	PAE,0.71; CMC,0.29	0.40	62.2	155	0.401	5.66	0.660	333	30.7	1.86	0.086	95.5	5.75	1.39	1.50	0.108	25.0	Instantaneous
12	PAE,0.59; CMC,0.41	0.7	59.5	148	0.402	5.68	0.397	306	7.8	1.71	0.107	93.4	3.45	1.28	1.40	0.066	23.3	Instantaneous
13	PAE,0.5; CMC,0.50	1.0	65.9	161	0.410	5.51	0.584	349	49.0	1.91	0.215	118	4.50	1.42	1.32	0.152	22.0	Instantaneous

[a]Extensional stiffness.

Previous results with the CMC/PAE complex showed a lack of sizing (water resistance) among treated papers. This is not surprising considering the polar nature and relatively high surface energy of the additives. Accordingly, an examination was made of sizeability using classified pulp. Results in Table III show that such papers can be readily sized with dispersed rosin size in the presence of alum at pH 5.0 - 5.2 or with synthetic size at pH 8-9 with a relatively small decrease in tensile properties. Since the amount of sizing agent used in these tests produced hard sizing, it would be expected that the decline in strength could be minimized at lower sizing agent additions, particularly in the case of dispersed rosin size.

TABLE III

THE EFFECT OF SIZING AGENTS ON THE EFFICIENCY OF CMC/PAE COMBINATIONS

(Classified Unbleached Kraft - Cook #2, 47.2% Yield; Kappa No. 34.3)

Set No.	Additives, % Based on Fiber	Basis Wt., g/m^2	Thickness, µm	Apparent Density, g/cc	Dry Strength Properties: Breaking Length, Km	SD	Dry Strength Properties: Et[c], kg/cm	SD	Moist Strength Properties: Breaking Length, Km	SD	Moist Strength Properties: Et[c], kg/cm	SD	Moist Tensile Factor	Wet Breaking Length, Km	SD	Wet Tensile Factor	Sizing (Water Drop Test) Sec.
8	Blank Controls[a]	60.9	158	0.386	2.90	0.165	209	17.4	1.34	0.100	96.5	11.0	1.0	0.06	0.006	1.0	Instantaneous
9	Controls, PAE,1.0[a]	63.2	163	0.388	4.47	0.358	273	12.3	1.76	0.189	104	13.9	1.31	0.75	0.034	12.5	Instantaneous
14	PAE,1.0; CMC,0.4[a]	63.9	157	0.406	6.63	0.471	344	20.7	3.44	0.133	124	16.4	2.57	1.24	0.049	20.7	Instantaneous
15	PAE,1.0; CMC,0.4; Alum, 1.0; Dispersed rosin size, 0.5[b]	65.7	162	0.407	5.29	0.430	345	17.1	3.15	0.310	143	16.5	2.35	1.22	0.118	20.3	1800+
16	PAE,1.0; CMC, 0.4; Alkyl succinic anhydride, 0.25[a]	62.3	148	0.421	5.86	0.662	326	31.9	3.32	0.315	124	18.8	2.48	1.05	0.113	16.7	1800+

[a]pH 8-9
[b]pH 5.0-5.2
[c]Extensional stiffness

A subsequent unit of work examined the effect of fines on the efficacy of two additive combinations (CMC/PAE and PVE/PAE/PAA) which were previously shown to provide high moist and wet tensile factors. Results are recorded in Table IV. In general, handsheets formed from the whole pulp were stronger than those from the classified pulp. Since moist and wet tensile factors are determined by dividing the tensile result by that of the blank controls, the notably higher strength of the controls tended to diminish moist and wet tensile factors for the whole pulp compared to those of the classified pulp. In effect, the combinations of additives were more effective relative to the controls in the classified pulp than in the whole pulp. Conceivably the strength additives were preferentially retained by the fines in the whole pulp and were not as available for interfiber bonding as in the classified pulp or, alternatively, variations in fines retention may have occurred with addition of the strength agents. The results suggest that these additives will be effective in lightly refined pulps which should benefit drainage and machine speed.

TABLE IV

A COMPARISON OF WHOLE AND CLASSIFIED PULPS WITH RESPECT TO ADDITIVE EFFECTIVENESS

(Softwood Unbleached Kraft - Cook #2, 47.2% Yield; Kappa No. 34.3)

Set No.	Additives, % Based on Fiber	Basis Wt., g/m²	Thickness, µm	Apparent Density, g/cc	Dry Strength Properties: Breaking Length, Km	SD	Dry Strength Properties: Et[a], kg/cm	SD	Moist Strength Properties: Breaking Length, Km	SD	Moist Strength Properties: Et[a], kg/cm	SD	Moist Tensile Factor	Wet Breaking Length, Km	SD	Wet Tensile Factor	Sizing (Water Drop Test) Sec.
	UNCLASSIFIED PULP																
17	Blank Controls	63.2	148	0.426	4.30	0.219	326	11.7	2.30	0.118	148	8.0	1.00	0.115	0.005	1.0	Instantaneous
18	Controls; PAE,1.0	63.1	146	0.431	6.42	0.412	345	38.3	3.69	0.095	140	10.1	1.60	1.18	0.033	10.3	Instantaneous
19	PAE, 1.0; CMC,0.4	64.5	146	0.443	6.74	0.308	379	9.5	4.14	0.168	152	10.8	1.80	1.28	0.044	11.1	Instantaneous
20	1:1 Blend PVA:PAE, 1.0; PAA, 1.0	69.8	154	0.453	6.65	0.231	450	27.5	4.28	0.232	190	12.7	1.86	1.38	0.063	12.0	Instantaneous
	CLASSIFIED PULP																
8	Blank Controls	60.9	158	0.386	2.90	0.165	209	17.4	1.34	0.100	96.5	11.0	1.0	0.06	0.006	1.0	Instantaneous
9	Controls, PAE,1.0	63.2	163	0.388	4.47	0.358	273	12.3	1.76	0.187	104	13.9	1.31	0.15	0.034	12.5	Instantaneous
14	PAE,1.0; CMC,0.4	63.9	157	0.406	6.63	0.471	344	20.7	3.44	0.133	124	16.4	2.57	1.24	0.049	20.7	Instantaneous
21	1:1 Blend PVA:PAE, 1.0; PAA, 1.0	66.6	163	0.408	5.25	0.298	386	18.9	3.50	0.238	164	13.7	2.61	0.91	0.047	15.2	Instantaneous

[a]Extensional stiffness.

FUTURE WORK

Chemical analysis of selected treated papers is underway in an effort to determine retentions. In this direction, efforts will be made to determine the form or composition of the retained multicomponent complexes. This may be complicated by the formation of covalently bonded structures which resist extraction by commonly used solvents. The effectiveness of PVA/cationic additive combinations will be re-examined taking economic factors into account. The most efficient multicomponent systems will subsequently be examined in high yield pulps. The repulpability of papers containing multicomponent complexes will be examined and, ultimately, new chemical approaches for improving the moisture tolerance of paper will be considered.

LITERATURE CITED

1. Espy, Herbert H. TAPPI Proceedings, 1983 Papermakers, Conference, pp. 191-195.

J. J. Becher
2/10/84

SECTION 2

FUNDAMENTALS OF INTERNAL STRENGTH ENHANCEMENT

Fundamentals of Bonding in Conventional Pulps

INTRODUCTION

A specific objective of this project is to improve the strength of the individual fiber/fiber bond. To this end we are proceeding along two fronts. (1) Continuing the work presented in the last Status Report, we are determining the locus of failure of the fiber/fiber bond. (2) In anticipation of the potential of the instrument being constructed under Project 3527, we are carrying out exploratory measurements of the strength of fiber/fiber bonds. The results are presented below.

RESEARCH RESULTS

To better observe the failure process of the fiber/fiber bond, we have constructed a device to permit straining the bond in situ in the scanning electron microscope (SEM). The bonded fiber pair is coated with gold/palladium, installed in the SEM, and strained to failure. Micrographs are taken before and after failure. Surfaces with no coating are taken to be the formerly bonded areas. These are readily apparent due to "charging" effects of the electron beam. It is not possible to resolve features on the uncoated surfaces. Therefore, the strained fibers are removed from the SEM, coated again, this time with aluminum, and reinstalled in the SEM. Using the EDS (energy dispersion spectroscopy) mode, we can relocate those areas with no gold/palladium coating corresponding to the formerly bonded areas. Morphological features (fibrils, compressions, etc.), which can be matched with those on the fibers before removal for the second coating, provide a check that we are indeed examining the bonded region.

To date we have tested three types of fibers:

a) unrefined bleached kraft (loblolly pine)

1. springwood

2. summerwood

b) southern pine bleached kraft beaten to 300 CSF.

The unrefined fibers have virtually undamaged surfaces. Hence wall fracture during bond failure is readily apparent. For both springwood and summerwood we found evidence for failure either at the interface or within the cell wall depending upon the particular fiber pair. No pattern for failure mode was obvious, although failure at the interface was prevalent.

Determination of the mode of failure for the refined fibers was ambiguous. Damage to the fiber surface due to refining was widespread. Discerning whether morphological features in the region of a former bond were due to wall fracture was difficult. However, in many cases a residual indentation where the fibers had crossed was apparent. For some of these, debris in the region appeared to be from the other fiber. Further study to confirm this failure mode and its prevalence is indicated.

At this point we do not have enough evidence to state with assurance which is the dominant mode of failure, especially for the important case of refined fibers. We feel, however, that with further development of our technique this information will be forthcoming.

Because some bonds appeared to rupture at the interface and appeared (qualitatively) weak during straining, we wondered whether there were discrete populations of strong and weak bonds. Accordingly, a number of fiber/fiber bonds were strained to failure in the IPC Fiber Load Elongation Recorder (FLER). Initial results for the springwood, unrefined fibers were only 0.07 ± 0.02 g. Values for the refined fibers were also low. We then modified our method of bond preparation. After wet-pressing the crossed fibers at 100 psi for five minutes, we dried the samples under pressure (0.8 psi) in an oven at 105°C for 90 minutes. This pressure is similar to that experienced by the sheet as it is held against a dryer cylinder by a dryer felt. This method usually produced substantially stronger bonds. The results are listed in Table V.

TABLE V

STRENGTH OF FIBER/FIBER BONDS†

Fiber	Force at failure, g	Fiber	Force at failure, g
Springwood	0.48	Summerwood	0.63
Springwood	0.13	Summerwood	0.08
Springwood	0.61	Summerwood	0.04
Springwood	0.17	Summerwood	1.30
		Summerwood	0.57
Refined	0.59	Summerwood	0.48
Refined	0.12*	Summerwood	0.72

†Dried under pressure

A rather broad variation can be noted. Part of this is because the bonded area varies from one fiber pair to the next. Indeed the sample marked with an asterisk was composed of a fiber of normal width crossed with an abnormally narrow one. However, most of the fibers were of similar width; the variation must be attributed to different numbers of hydrogen bonds formed in the bonded area. There does appear to be two populations of strength, $\geq$ 0.5 g and < 0.2 g.

At this time we were experiencing problems with the curing of the cement used to attach the fibers to the apparatus. With a change to a new cement we continued the studies. The results are presented in Table VI.

TABLE VI

STRENGTH OF FIBER/FIBER BONDS†

Fiber	Force at failure, g
Summerwood	0.55
Summerwood	0.45
Summerwood	0.33
Summerwood	0.54
Summerwood	0.02
Refined	0.52
Refined	0.69
Refined	0.90
Refined	1.68*
Refined	1.28*

†Dried under pressure

The bonds formed with the refined fibers are appreciably stronger than those from the summerwood. Although the species of pine may not be identical for the two samples, they are certainly similar. It would be expected that the refined fiber would be more conformable and hence provide more hydrogen bonds per unit area of bond in agreement with the enhanced strength above. For the two samples marked with an asterisk a small piece of pulp fines was observed to be present at the crossover point and likely contributed to the enhanced strength. This is in agreement with the finding of others that the addition of fines to a classified furnish improves sheet strength.

FUTURE WORK

These results suggest that it is feasible to obtain bond strengths from single crossed fibers. The more sensitive instrument being developed under Project 3527 will improve the accuracy of the measurement. The bimodal population of bond strengths suggests that it would be advantageous to measure the bond strength on the actual samples observed in the SEM. A correlation of strength with mode of failure could indicate the conditions needed to improve strength. The next step is to develop the techniques necessary to provide this correlation.

R. A. Stratton
2/10/84

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3396

MECHANICS OF FLUTING

February 10, 1984

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)

PROJECT TITLE: MECHANICS OF FLUTING

PROJECT STAFF: W. J. Whitsitt

PROGRAM GOAL: Identify the critical parameters which describe converting and end-use performance.

Date:	Feb. 16, 1984
Budget:	$80,000
Period Ends:	6/30/84
Project No:	3396

PROJECT OBJECTIVE:

To improve the performance/cost ratios of medium by modifications in medium, machine and operational conditions.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS LAST PERIOD: (March 1983 - September 1983)

Our research is focused on making improvements on medium properties to recover the strength losses which occur in fluting and to enhance end-use performance properties. The improvements are directed to increasing flat crush and the medium contribution to the ECT strength of combined board, and hence, to allow trade-offs between performance and cost.

(1) Present results indicate that the retention of compressive strength during fluting is favored by a high out-of-plane modulus (E_Z/ρ) relative to E_X/ρ, and by high densities. Retention will be adversely affected by increasing basis weight if density is held constant.

(2) Densification of medium by means of wet pressing make substantial increases in flat crush and the cross direction ECT. These improvements are due to the higher compressive strengths and elastic stiffness obtained at higher wet pressing levels.

(3) With regard to forming, simulation experiments show that bending and shear strains such as are encountered during fluting decrease fiber bonding, and hence, reduce the elastic stiffnesses. As a result the compressive strength of the medium is reduced during fluting as has been observed in past work.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

Our research is focused on making improvements on medium properties to recover the strength losses which occur in fluting and to enhance end-use performance properties. The improvements are directed to increasing flat crush and the medium contribution to the ECT strength of combined board, and hence, to allow trade-offs between performance and cost.

(1) At a given basis weight retention of compressive strength is favored by
  a. lower E_x/E_y ratios
  b. higher density at a given basis weight
  c. greater radius of curvature of the fluting rolls.

(2) Densification has a favorable effect on retention because it reduces thickness (hence lower bending strains), improve E_z at a faster rate than E_x and improves most strength properties.

(3) Substantial increases in combined board ECT and flat crush can be accomplished via improved wet pressing.

(4) STFI tests are a better predictor of combined board performance than ring crush when evaluating the effects of densification.

(5) While densification reduces porosity and water receptivity we have obtained acceptable bonding on the corrugator for all materials studied to date. Current work will evaluate runnability and bonding at high corrugating speeds.

All of these are discussed in the attached report.

PROJECT TITLE: Mechanics of Fluting	Date: 3/18/83
PROJECT STAFF: W. J. Whitsitt	Budget: $80,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use	Period Ends: 6/30/84
	Project No: 3396
PROGRAM AREA: Improved converting processes and converted products.	Approved by VP-R: [signature]

PROGRAM GOAL: Identify the critical parameters which describe converting and end-use performance

PROJECT OBJECTIVE:

To improve the performance/cost ratios of medium by modifications in medium, machine and operational conditions.

PROJECT RATIONALE:

In our past work we have established how medium properties affect and are affected by forming. Key findings show that the formed medium exhibits a 40+% loss in MD and a 20+% in CD compressive strength. These losses in compressive strength affect the subsequent performance of the medium in the corrugated products, e.g., in flat crush. The bending stresses imposed during forming appear to be instrumental in decreasing the compressive potential of the medium. By optimizing papermaking factors it should be possible to make mediums with better forming and end-use compressive properties. These will provide ways to reduce costs by trade-offs between performance and manufacturing costs.

In forming operations such as fluting, creasing and folding, board is subjected to high bending stresses. Because of the high stresses in fluting the properties of the medium are degraded. In other bending operations such as creasing the board local degradation is necessary to achieve successful folding performance in high speed operations. Analysis of board behavior under high flexural and shear stresses will determine the properties needed for performance and lead to papermaking ways to maintain more consistent quality.

RESULTS TO DATE:

Our research has focused on five main areas. They are (1) The effects of forming on the loss of compressive potentials, bonding, and other properties; (2) The relative importance of tension and bending stresses on compressive potential of the medium; (3) Flute geometry vs forming conditions; (4) Flat crush performance vs forming and the development of flat crush models; and, (5) Development of basic information on medium properties involved in forming. Current results show that densification of a corrugating medium furnish, by means of improved pressing, substantially increases flat crush strength by 35-40% over present commercial mediums. The experimental mediums have higher compressive strength and lose less compressive strength in the fluting process. Thus, both factors, higher strength and less loss, contribute to the high flat crush values.

Initial results indicate that the recovery of strength during fluting is favored by high transverse moduli such a $E_{z/\rho}$ and lower thickness. High transverse moduli would be expected to help the sheet resist delamination during forming and, hence, retain compressive strength.

PLANNED ACTIVITY FOR THE PERIOD:

We are continuing investigations directed to clarifying the reasons for the improvements obtained in current work. This includes consideration of the best way to optimize densification, wet straining and fiber orientation to achieve the desired improvements in the basic elastic and other properties to enhance formability. Wet straining should be important because it significantly affects $E_{z/\rho}$ as well as other sheet properties. We also plan to consider other means for improvement including fiber furnish, additives and sheet structure such as multiply constructions.

We also plan to use finite element analysis technique coupled with appropriate material data to follow the stresses and strains developed in flexure under various curvature conditions up to failure. Initial modeling will focus on conditions encountered in fluting operations

POTENTIAL FUTURE ACTIVITIES:

As corrugating speeds increase we see more need to extend our present knowledge of forming into medium and machine factors which affect this stability of the fluted shape, e.g. high-lows. The fluted shape becomes less stable as the fracture speed is approached and hence, appears to be another manifestation of the degradation of the medium by the forming stresses. Initially this will require in-depth consideration of medium behavior under high tensile and compressive stresses in relation to the labyrinth geometry.

Status Report

MECHANICS OF FLUTING

Project 3396

INTRODUCTION

The objective of the program is to determine the impact of the fluting process on board strength and to use this knowledge to improve board strength while maintaining runnability. This objective requires consideration of medium properties, operational conditions on the corrugator, and flute geometry. Our present work is focused in making improvements in medium properties to prevent the strength losses in fluting and hence, improve performance.

In the uncorrugated state medium is made to have certain strength properties. However, in the fluting process we lose about 40% of the MD and 20% of the CD compressive strength of the medium. These losses occur due to the high bending strains imposed on the medium as it is fluted and are aggravated by the high web tensions in the fluting labyrinth. By reducing these losses in strength we could achieve significant savings in the manufacture of medium.

Our target goals are to increase the compressive strength of medium in both directions, while improving formability. Such improvements will increase flat crush and the contribution of the medium to combined board edgewise compressive strength (ECT).

Compressive strength is highly related to the elastic moduli of the sheet, as discussed in past reports. High compressive strength is favored by high moduli in the plane of the sheet (E_x and E_y) and by high out-of-plane moduli (E_z, G_{xz} and G_{yz}). Densification to increase fiber bonding is an effective way to increase all of these moduli and hence, compressive strength.

In our past and current work we have determined that higher wet pressing improved compressive strength retention and most physical characteristics of the medium. This work has been carried out on both normal (26 lb) and heavy weight (40 lb) oriented semichemical sheets made on the Formette former. The improvements obtained via increased wet pressing at both basis weight levels are briefly summarized in the text.

Our corrugating trials on the experimental sheets have been carried out at low speeds (ea. 200 fpm) due to experimental limitations. The experimental sheets corrugated well and no bonding, high-low, or fracture problems were encountered. However, we need to establish whether densification of the medium will affect high-speed runnability. Because of their superior strength and lower thickness, the densified sheets should be better able to resist the brake tension and bending stresses in the forming labyrinth. Thus such mediums should be less prone to fracture and may exhibit less proclivity to form excessive high-lows. Densification does reduce porosity and water receptivity which could affect bond development at high corrugating speeds. Accordingly we are in the process of evaluating the high speed runnability of densified mediums made on under various conditions. Our plans and available results are included in this report.

Fluting Performance of Densified Mediums

In our wet pressing work we have made orientated sheets from a 75% semichemical/25% softwood furnish over a range of densities from about 500 to 1100 kg/m^3 (based on IPC compressible caliper tests). To obtain an initial evaluation of the corrugating performance the 26 and 41 lb experimental sheets were spliced into a "carrier" medium and made into single-faced boards at a speed of about 200 fpm.

Our past and current work indicates that the retention of compressive strength is approximately related to the elastic stiffnesses of the sheet, basis weight and density as follows. (See also Fig. 1.)

$$RR \sim 1 - (K/R)(E_X/E_Z)^{1/4}\ W/\rho \quad (1)$$

where RR = retention ratio (ratio of compressive strengths of fluted to uncorrugated medium)
E_X = MD Young's modulus
E_Z = out-of-plane Young's modulus
W = basis weight
ρ = density
R = radius of curvature of the fluting rolls
K = constant

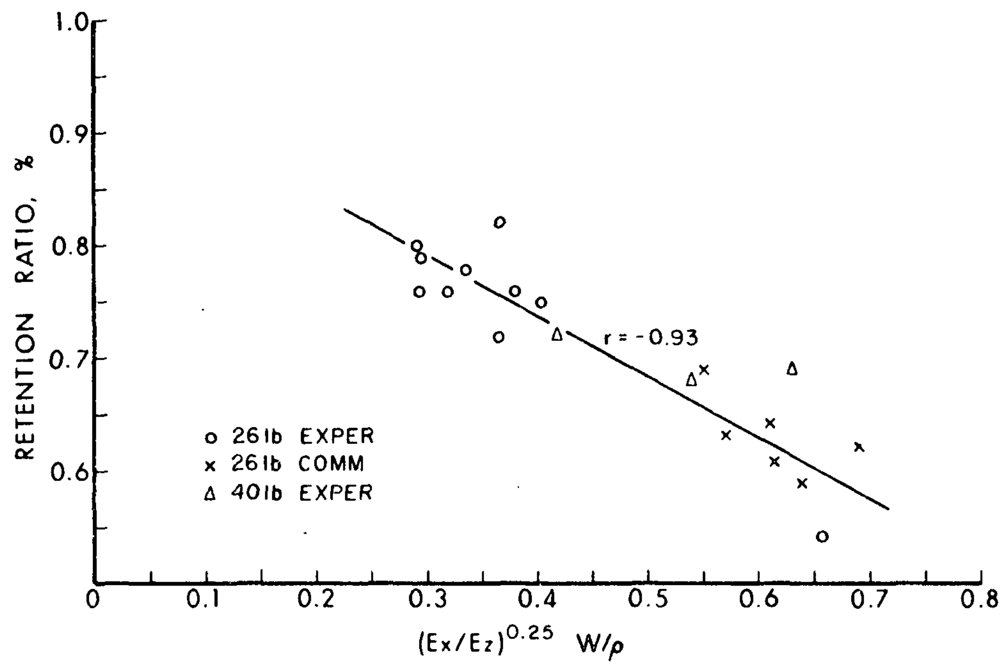

Figure 1. Retention of compressive strength during fluting depends on elastic stiffnesses, (E_X/E_Z) basis weight (W) and density (ρ).

At constant basis weight higher strength retention can be achieved via higher wet pressing to improve fiber bonding. Higher wet pressing densifies and tends to increase E_Z at a faster rate than E_X. Figure 2 shows that increasing density increased the retention of compressive strength for both 26 and 40 lb mediums. The improvements in retention were somewhat less for the 40 lb mediums than for the 26 lb mediums because of the higher thicknesses of the 40 lb sheets.

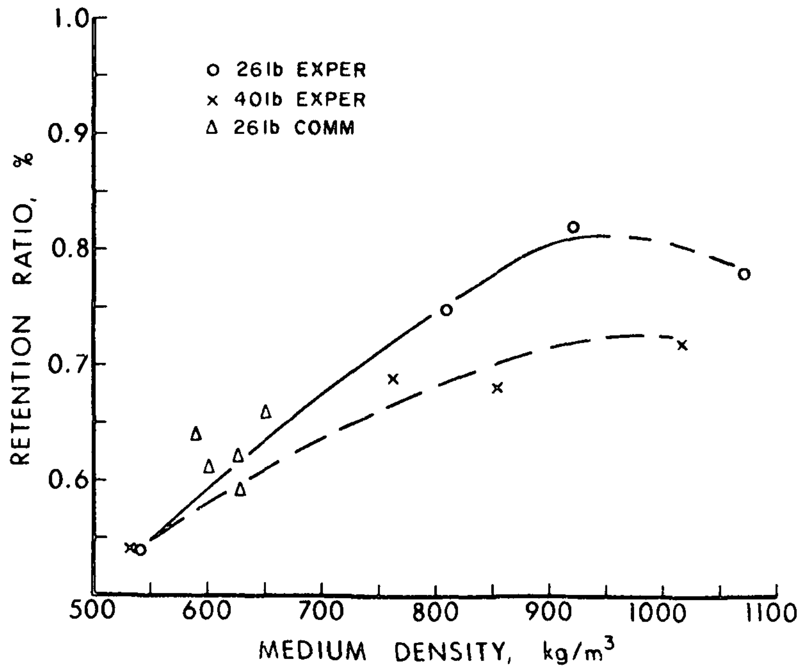

Figure 2. Effect of density on retention of compressive strength during fluting.

Because densification improved most strength properties as discussed later in the text, flat crush strength increased substantially as density increased (Fig. 3). At the higher densities they were also greater than obtained with most present commercial mediums. These improvements in flat crush can be attributed to better retention during fluting and the higher MD compressive strengths of the densified sheets.

Compression tests carried out on the single-faced board shows that increasing medium density markedly increases the contribution of the medium to

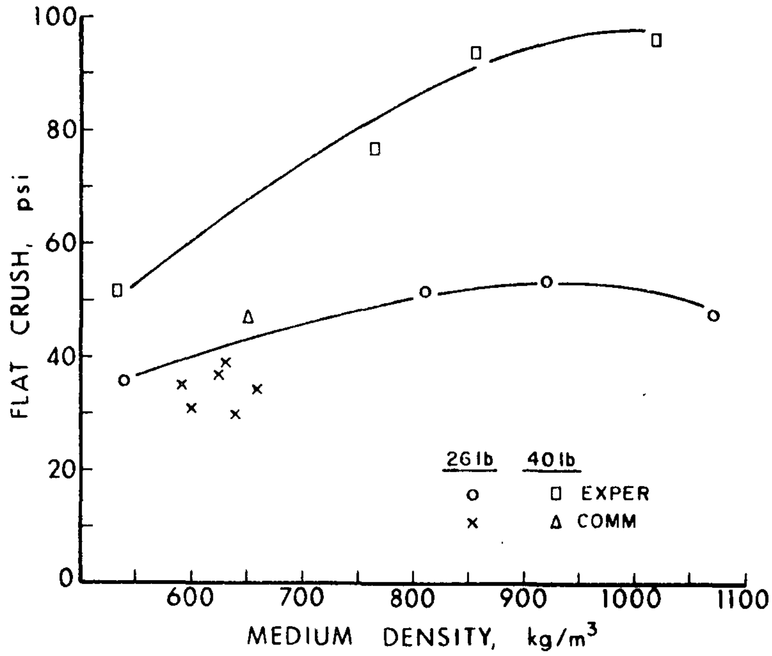

Figure 3. Increasing medium density improves flat crush.

CD ECT (Fig. 4) as a result of the higher CD compressive strength of the medium. The results in Fig. 4 are based on a ring type of test we often carry out on single-faced board, however conventional ECT tests made on manually double-backed samples confirm these trends.

We have compared the flat crush and ECT results shown in Figs. 3 and 4 for the 40 lb medium with the STFI and ring crush results on the uncorrugated medium. Comparison of Fig. 5 with Fig. 3 shows that increasing medium density increased the MD STFI and flat crush results in a similar way, however the ring crush results passed through a maximum at about 750-800 kg/m^3. A similar situation prevails when the CD STFI and ring crush results are compared with the single face ECT results (compare Fig. 4 and 6). Thus the STFI results were more indicative of the fluted performance of the medium than ring crush in this instance because the ring crush tests may be unduly influenced by the thickness changes accompanying densification. The results indicate that care must be used in selecting an appropriate compressive strength test when evaluating the potential effects of papermaking changes.

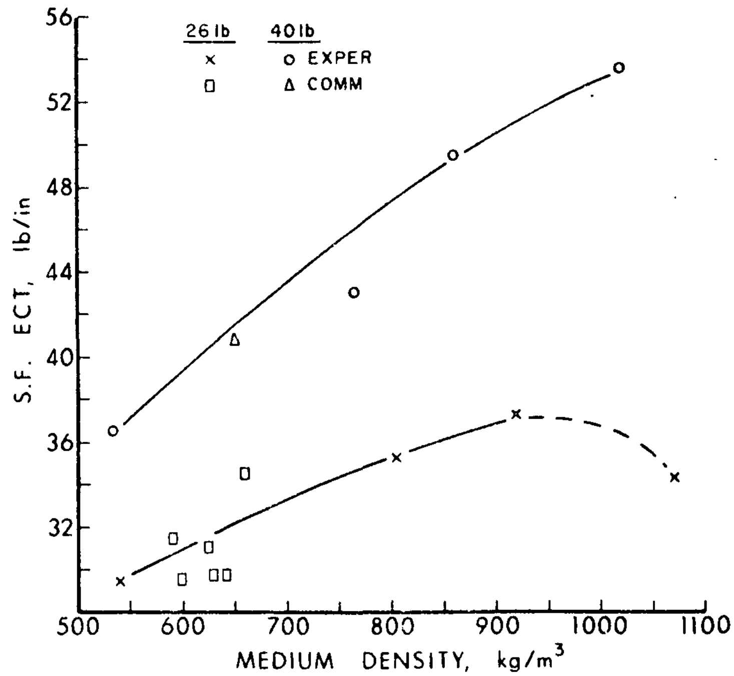

Figure 4. Increasing medium density improves ECT strength.

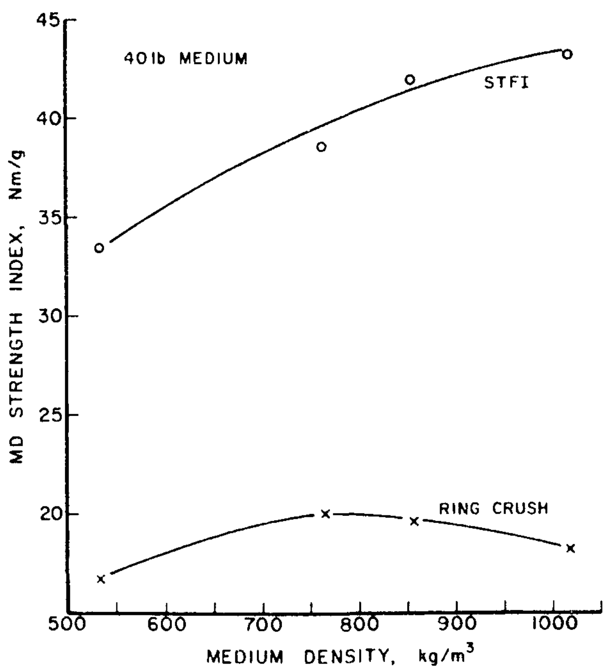

Figure 5. MD STFI and ring crush show different trends with increasing medium density.

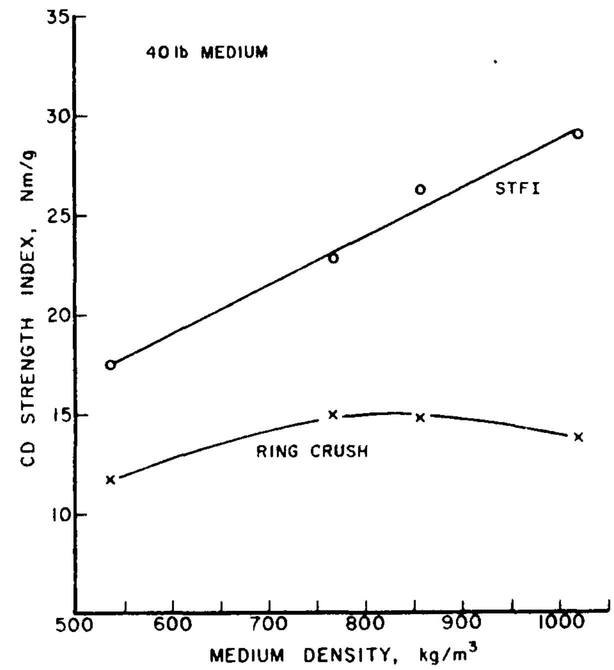

Figure 6. CD STFI and ring crush show different trends with increasing medium density.

As mentioned earlier all of the experimental and commercial mediums used as controls corrugated with no difficulties at the low speeds used. No bonding problems were encountered and the single face pin adhesion test values were at a high satisfactory level for all the medium (Fig. 7). The bonding aspects of runnability need further consideration, however, because of the reductions in receptivity and porosity which accompany densification. We have work in process to explore the high speed runnability and bonding of densified mediums as discussed in later pages.

Effects of Densification on Medium Properties

As discussed in previous reports higher wet pressing produces substantial increases in the STFI compressive and tensile strengths of medium (Figs. 8 and 9). The higher compressive strengths obtained by increased wet pressing resulted in the higher flat crush and ECT results obtained on the corrugated board. The rougher sheet surface quite similar to the other side of the sheet. It is believed the latter condition would be more realistic. We are not certain this pressing/drying change accounts for the difference in compressive strength indexes between sheet weights, however, it deserves further attention because it may point the way to other avenues of strength improvement.

The specific in-plane and out-of-plane elastic stiffnesses increased with increasing density (Fig. 10). From past work we know that compressive strength is dependent on the product of $E_x^{3/4}E_z^{1/4}$ and $E_y^{3/4}E_z^{1/4}$. Because densification increased all three stiffnesses it would be expected that compressive strength would increase as illustrated in Fig. 8.

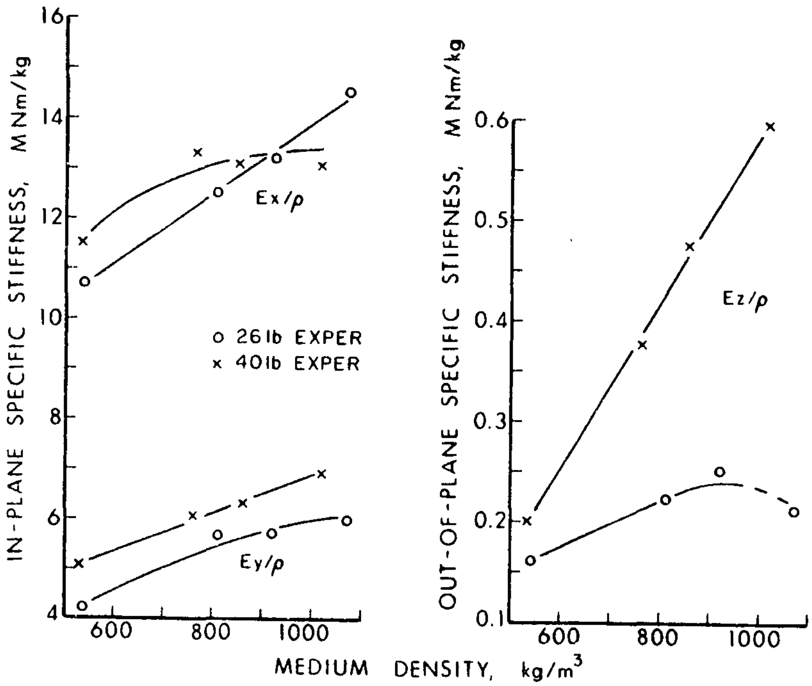

Figure 10. Effect of density on elastic stiffnesses.

It may be noted that the 40 lb sheets tended to exhibit higher in-plane and markedly higher out-of-plane stiffnesses than the 26 lb sheets. These stiffness differences help account for the differences in compressive strength between sheet weights and are apparently related to pressing differences noted above.

High Speed Runnability

The superior medium strengths achieved by better wet pressing should help the medium run at high speeds without flute fracture and, perhaps reduce high/low proclivities. Normally high-lows increase dramatically as speeds approach the point where fractures first become visible. In this sense high-lows are another manifestation of sheet degradation in the fluting process and superior strength should help.

It is not clear whether densification will necessarily result in severe bonding problems during corrugating. Increased wet pressing does make the sheet less receptive to water and less porous (Figs. 11 and 12). Commercial mediums do exhibit wide ranges in these properties. The ranges shown are based on data for 35 commercial mediums of all types. In general these mediums corrugated satisfactorily without fracture and exhibited good single-face pin adhesion strengths.

Accordingly we have initiated work directed to determining how experimental densified mediums made under various pressing, drying and orientation conditions will perform at high corrugating speeds. Performance will be evaluated in terms of bonding, high-lows and flute fracture. These experiments should help determine if densification will have major adverse effects in high-speed runnability.

For this purpose we have made 26 lb sheets at their density levels and two degrees of surface furnish. In addition sheets have been made at three levels of MD/CD orientation at one density. We are corrugating these sheets at speeds

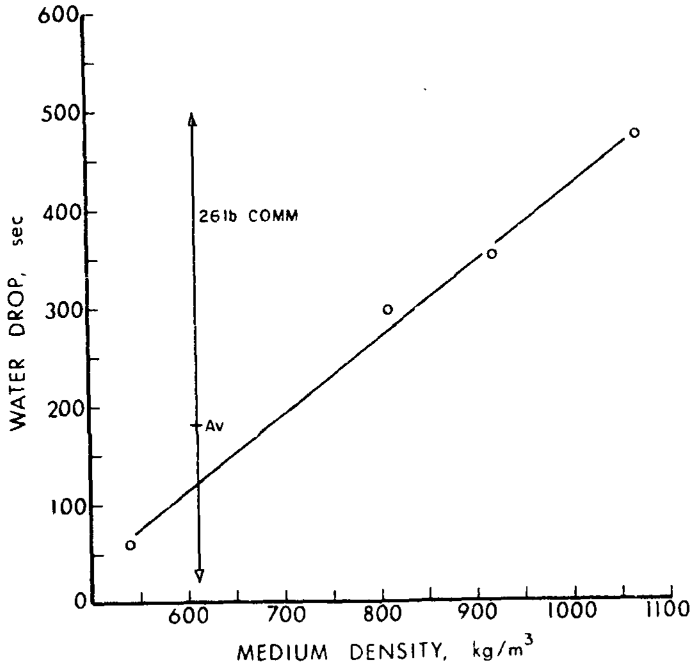

Figure 11. Effect of density on medium water receptivity.

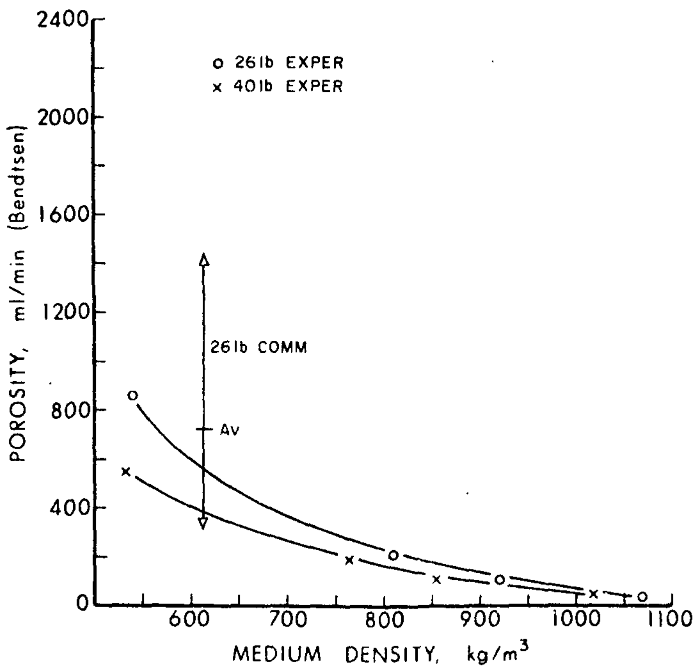

Figure 12. Effect of medium density on porosity.

of 400, 550 and 650 fpm along with selected commercial "controls". The resulting single-face boards are being evaluated for quality in terms of flute fracture, high-low, adhesion, flat crush and ECT.

To provide baseline corrugating performance data we have recently carried out trials at a series of corrugating speeds up to 800 fpm using a commercial 26 lb semichemical medium. On our pilot corrugator pin adhesion strengths begin to decrease rapidly at speeds above about 500 to 600 fpm (Fig. 13). As the pin adhesion strengths decrease the bonds become more brittle. ECT strengths hold constant up to speeds of about 650-700 fpm and then begin to decrease rapidly due to the poor adhesion (Fig. 14). More heat and steam on both liner and medium would be required to achieve satisfactory adhesion at the higher speeds even with current commercial mediums on our pilot corrugator. For our present trials we selected the 400 fpm speed to place us on the adhesion plateau; the 650 fpm occurs in the region where bond strength begins to decrease rapidly.

Keeping the above in mind, preliminary observations on the corrugating performance of the experimental sheets indicates that flute fracture problems should not occur due to densification. With very highly densified mediums bonding on the corrugator appeared to become deficient in the 400-550 fpm speed range depending somewhat on the surface roughness. This suggests that means for adjusting water receptivity and roughness along with the heat conditions on the corrugator may need attention.

Concurrent with the above work we are developing baseline information on how the frictional characteristics of medium are affected by temperature and moisture content. The frictional characteristics greatly affect the tensions developed in the medium during forming. Mediums with high frictional

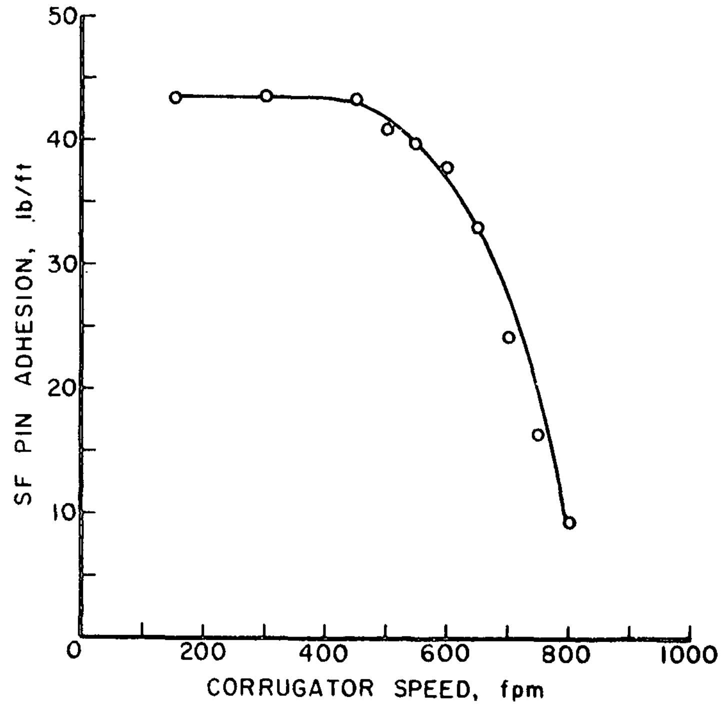

Figure 13. Effect of corrugating speed on pin adhesion for 26 lb commercial medium combined with 42 lb liner.

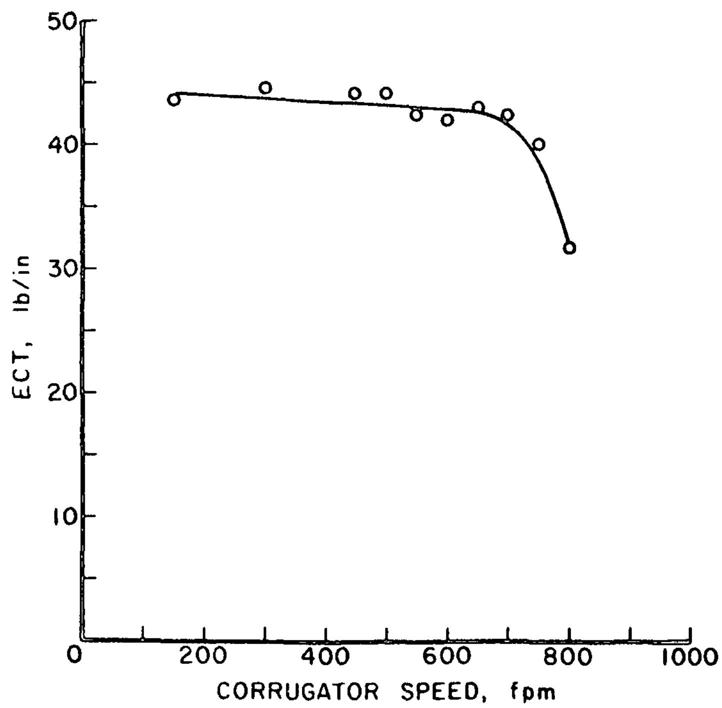

Figure 14. Effect of corrugating speed on ECT for 26 lb commercial medium combined with 42 lb liner.

coefficients will fracture at low corrugating speeds, depending on the brake tension applied. In general, recycled fiber mediums exhibit lower frictional coefficients than semichemical mediums, due apparently to residual waxes in the sheet. Modest increases in temperature make further reductions in the frictional coefficient of recycled fiber medium. Semichemical mediums tend to exhibit high frictional coefficients which remain relatively constant up to temperatures of 150-200°F. Substantial decreases in friction from about 0.5+ to as low as about 0.3 occur when the steel reference surface temperature is raised to about 350°F. However, the degree of friction reduction with temperature appears to vary depending on the semichemical mill source.

This work will help us assess high speed runnability in the current work and has application in our allied work on improvements in medium preconditioning on the corrugator.

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3469

COMPRESSIVE STRENGTH

February 10, 1984

PROJECT SUMMARY: (June 31, 1983-July 1, 1984)	Date: Feb. 18, 1984
PROJECT TITLE: COMPRESSIVE STRENGTH	Budget: $85,000
PROJECT STAFF: W. J. Whitsitt/J. F. Waterhouse	Period Ends: 6/30/84
PROGRAM GOAL:	Project No.: 3469

Identify critical parameters which describe converting and end-use performance and promote improvements in cost/performance ratios.

PROJECT OBJECTIVE:

To establish practical methods for enhancing compressive strength during paperboard manufacture.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS PAST PERIOD: (March 1983 - September 1983)

1. We have estimated the compressive strength potential of wood pulp and find it to be 30 to 80% larger than values obtained for high density handsheets. Although the approach may be questioned, the results suggest that current papermaking practices do not fully utilize the strength potential of the pulp.

2. The effects of pulp yield on compressive strength have been studied. A high yield (89%) sulfonated wood chip pulp was found to give higher compressive strengths than a conventional kraft pulp.

3. The effect of fines and compressive strength was studied by adding fines uniformly to the long fiber component of the furnish or by placing fines only in the core of the sheet.

4. The IPC Formette Dynamique sheet former has been modified to give superior sheet forming capabilities (compared to past experience).

5. A study of the wet press felt type on compressive strength revealed that blotters used in laboratory studies typically give significantly higher density and strength values than commercial wet pressing felts.

6. A consideration of compressive strength enhancement by polymer reinforcement shows that substantial improvement might be realized.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

1. Work concerning the compressive strength potential of several high yield pulps has been initiated.

2. Work concerning densification of medium and linerboard by wet pressing has continued, including the impact on bending stiffness.

3. The question of press felts and their impact on compressive strength will be investigated in student research (Tom Bither).

4. Another student (Paul Ruthven) will examine the impact of polymer reinforcement on compressive strength.

Date:	3/18/83
Budget:	$85,000
Period Ends:	6/30/84
Project No.:	3469
Approved by VP-R:	[signature]

PROJECT TITLE: Compressive Strength

PROJECT STAFF: W. J. Whitsitt/J. F. Waterhouse

PRIMARY AREA OF INDUSTRY NEED: Properies Related to End Use

PROGRAM AREA: Improved converting processes and converted products

PROGRAM GOAL:

Identify critical parameters which describe converting and end-use performance and promote improvements in cost/performance ratios.

PROJECT OBJECTIVE:

To establish practical methods for enhancing compressive strength during paperboard manufacture.

PROJECT RATIONALE:

Compressive strength is one of the most important end-use properties of linerboard, corrugating medium and other board products. Because of its importance, better ways to improve compressive strength are needed. Proposed changes in Rule 41 provide impetus for research on compressive strength. However, even in the absence of changes in Rule 41, future fiber and energy needs will encourage changes in board properties to place more emphasis on compressive strength. New research is expanding our knowledge of the compressive response of the board to papermaking processes and the relationship of compressive strength to the elastic stiffnesses governing failure. These developments indicate there are papermaking ways to approach the objective.

RESULTS TO DATE:

Edgewise compressive strength is known to be an important factor in container performance. Although it has received a considerable amount of attention in recent years, a clear understanding of how compressive strength may be optimized does not exist. The planned research will seek this understanding.

We have shown that compressive strength is highly related to the in-plane and out-of-plane elastic stiffnesses of paper. The relationship holds for commercial and experimental sheets made under many conditions. This development enhances opportunities to monitor compressive strength in the mill using ultrasonic techniques and is guiding improvement efforts.

Compressive strength is favored by high densification to increase bonding and high fiber compressive stiffness. Our results on oriented sheets indicate that compressive strength increases with refining but greater increases can be obtained by wet pressing to increase density. Within a practical range higher CD compressive strength can be achieved by decreased fiber orientation and/or increased CD restraint during drying.

PLANNED ACTIVITY FOR THE PERIOD:

We plan to continue investigations of the stress-strain behavior of board as functions of composition, structure, and process. This includes effects of fiber properties, pulping, bleaching, and the effects of papermaking variables; especially wet pressing, wet straining and drying. We will be focusing special attention on various types of high yield pulps made from both softwoods and hardwoods and exploratory work is planned to consider use of non cellulosic fibers and special strengthening additives. Practical methods for achieving suitable fiber-to-fiber bonding, sheet formation and directionality will be a necessary part of the work.

An important aspect of the work is the development of information on how the above papermaking factors affect the elastic stiffnesses which govern compressive strength and other properties. This will facilitate on-machine measurement applications.

POTENTIAL FUTURE ACTIVITIES:

On-line estimation of compressive strength and possibly applications to other strength properties of concern to end-use performance.

Status Report

COMPRESSIVE STRENGTH

Project 3469

INTRODUCTION

The importance of edgewise compressive strength of combined board to the top-to-bottom compressive loading performance of boxes has been demonstrated (1) and is generally accepted. It is also clear that the edgewise compressive strength of combined board must be related to the compressive strength potential of its components, i.e. the liner and medium. We will consider this point in more detail shortly, but first we will review our attempts to improve the compressive strength performance of the liner and the medium. Our focus has been and is continuing on a number of distinct but related fronts which may be broadly categorized as raw materials and papermaking process variables.

In the raw materials area we would like to determine the ultimate compressive stress potential of the fibers themselves, in order to determine how much of it is currently being utilized.

The importance of high yield softwood and hardwood pulps towards cost reduction strategies is well recognized and we are in the process of determining their impact on medium and liner compressive strength performance. The effectiveness of lignin as an intrafiber reinforcing polymer and its effect on compressive strength has yet to be determined. Furthermore, we are also interested in how effective other polymer systems or chemical agents might be. Towards this goal student research is underway to determine the affects of both intra- and interfiber polymer reinforcement on compressive strength and other board properties.

Paul Ruthven, M.S. Student, will address the problem of improving the compressive strength of paper by polymer reinforcement. The initial objective is the identification of a suitable polymer system(s) to be used in a study of interfiber versus intrafiber reinforcement of paper. This polymer system will be used to evaluate the improvement of the compressive strength of paper by different strategies of polymer placement. Handsheets reinforced with various polymer systems will be made and tested for compressive strength, tensile deformation behavior and in-plane/out-of-plane elastic constants. These handsheets will be tested for properties listed above. The strategies of polymer placement, namely, interfiber, intrafiber, and combined (interfiber and intrafiber) reinforcement will be evaluated with respect to improvement of the compressive strength of paper.

With regard to papermaking process variables, we have been concerned with refining, fiber orientation, wet pressing and drying with the main emphasis being on wet pressing and restraint during drying. In addition to continuing our endeavors in this area we are also trying to determine if there are any adverse effects of densification by wet pressing, for example on the runnability of medium.

We have also seen in previous work that the type of felt used in wet pressing may significantly affect board properties including compressive strength. This work raises fundamental questions concerning the consolidation process and forms the basis of another student independent study problem. Tom Bither, M.S. student, will attempt to determine the effect of wet-press felts on the physical properties of paper, and through this, gain a better understanding of the role of the felt in the consolidation of the wet web. Blotters, various felts and perforated plates will be used in pressing handsheets; the amount of press loading, the basis weight of the sheets and the amount of refining will be varied. Various testing methods and microscopic examination will be used to determine the effect of each of the felts on the structural and physical properties of the paper.

I. RAW MATERIALS

High Yield Pulps

In our last report we presented some preliminary results on the compressive strength, tensile, and elastic stiffnesses of high yield pulps. The results were for sulphonated spruce chips having a yield of approximately 89%. The variation of mean specific compressive strength with apparent density for freeness levels of 763, 714, and 540 C.S.F. is shown in Fig. 1. These pulps show a significant improvement in performance over the southern pine kraft pulp at 605 C.S.F. This is encouraging and suggests that very high yield pulps might be used in linerboard and possibly medium without impairing their compressive strength performance. We are currently measuring the performance and properties of other high yield pulps including a sulphonated southern pine (C.M.P.) and sulphonated red oak, prepared in our Chemical Sciences Division for another funded research project on high yield pulps. The sulphonated red oak has a yield of approximately 85%. A portion of this pulp was also given a chlorine and caustic post chemical treatment and it is expected that its yield will be reduced to 80%. The pulps have a high shive content and the rejects will require further refining to reduce the shive content to an acceptable level.

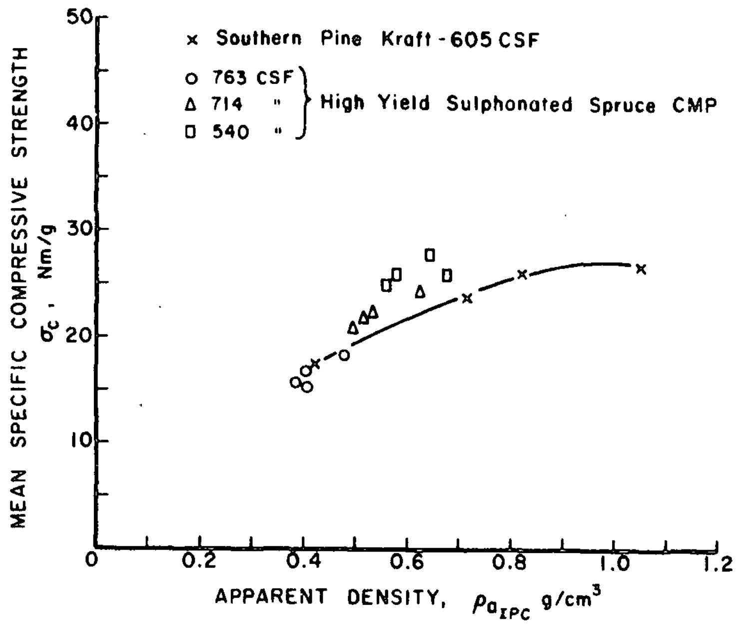

Figure 1. Compressive strength behavior of high yield pulps.

II. PAPERMAKING PROCESS VARIABLES

Wet Pressing

In earlier work we have reported the effects of refining, fiber orientation, wet pressing and restraint during drying on the compressive strength of both liner and medium. Densification of the medium and liner by wet pressing ensuring negligible shrinkage during drying was found to significantly improve compressive strength. Other aspects of densification by wet pressing are receiving attention in other projects including medium runnability and the effects of component densification on combined board edge compressive strength.

With regard to combined board compressive strength a series of experimental liners and mediums were made on the Formette Dynamique. The apparent density of the sheets was varied over a wide range and were held under full restraint during drying using the laboratory press-dryer at 195°F. The geometric mean specific compressive strength for the liners and medium as a function of density is shown in Fig. 2. We note a significant increase in the level of compressive strength for the high basis weight medium, e.g. at an apparent density level of 0.7 g/m^3 there is an increase in medium compressive strength of 10.9% when the basis weight of the medium is increased from 126.4 to 199.7 g/m^3. This is in part attributed to a difference in the felting method used for wet pressing.

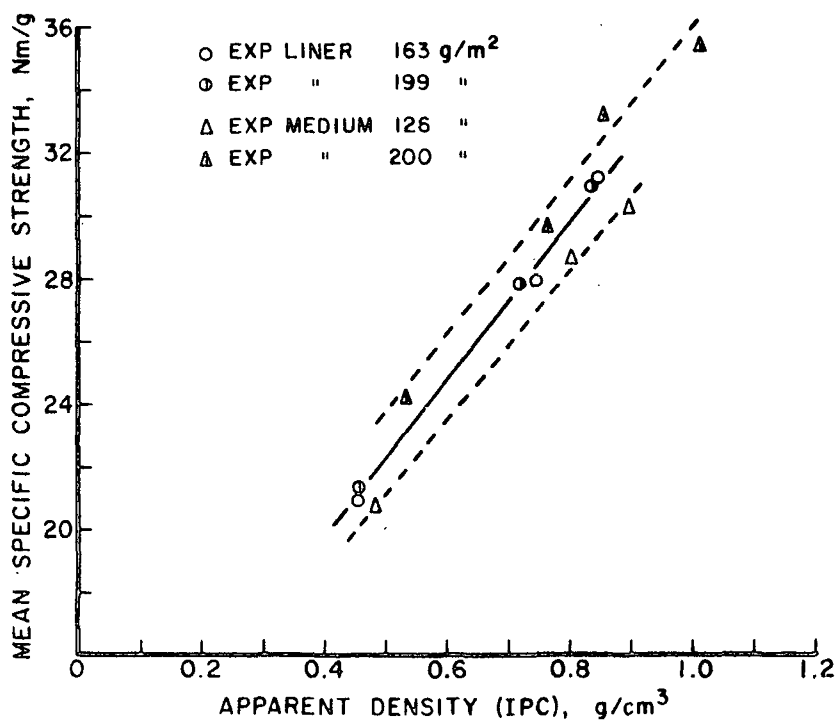

Figure 2. Compressive strength behavior of experimental liners and mediums.

Liner compressive strength results appear to be independent of basis weight as one would expect. In this case the felting method is the same for both basis weights (163 g/m^2 and 199 g/m^2).

We have also found in earlier results that the anisotropy of the sheet measured in a number of ways is affected both by the level of refining and wet pressing. In Fig. 3 we see that the anisotropy in compressive strength ($R = \sigma_{CMD}/\sigma_{CCD}$) decreases with increased densification by wet pressing for both the medium and liner samples. We have not yet determined whether this is also true for commercial medium and linerboard.

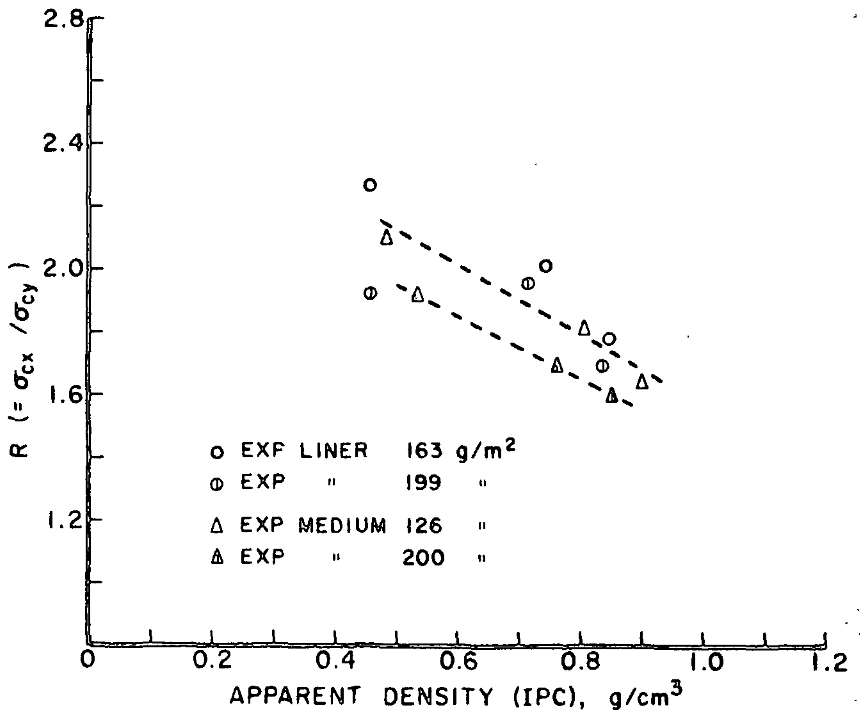

Figure 3. Compressive strength anisotropy of experimental liners and mediums.

The variation of cross machine direction specific compressive strength with apparent density for both liner and mediums is shown in Fig. 4. The CD compressive strength is particularly important for combined board edgewise compressive strength. We are interested in whether the improvement in component compressive strength is reflected in at least a proportionate increase in combined board compressive strength. The precise mechanisms and relationships are being examined in Project 3272.

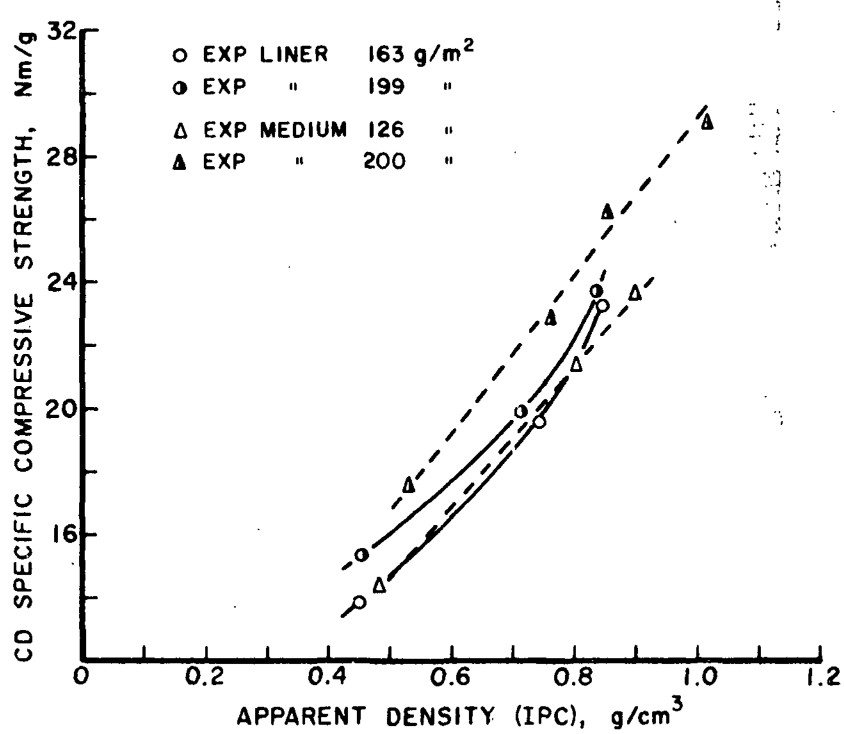

Figure 4. Cross machine compressive strength behavior of experimental liners and mediums.

REFERENCES

1. McKee, R. C., Gander, J. W., Wachuta, J. R., Compressive Strength Formula for Corrugated Boxes Paperboard Packaging, August 1963, p. 149-159.

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3272

ANALYSIS OF BOARD STRUCTURES

February 10, 1984

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)	Date: Feb. 16, 1984
PROJECT TITLE: ANALYSIS OF BOARD STRUCTURES	Budget: $100,000
PROJECT STAFF: R. A. Halcomb/W. J. Whitsitt	Period Ends: 6/30/84
PROGRAM GOAL: Identify the critical parameters which describe converting and end-use performance.	Project No.: 3272

PROJECT OBJECTIVE:

- To develop the relationships between container performance and critical combined board properties and between combined board properties and component properties.
- The short term ('83-'84) goal is to use combined board ECT models based on local buckling of the components to assess impact of densification and other papermaking factors on ECT strength.

PROJECT RATIONALE, PREVIOUS ACTIVITY and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS LAST PERIOD: (March 1983 - September 1983)

(1) The FPL model (Johnson, et al.) has been programmed for the Burroughs computer.

(2) The model has been used in conjunction with elastic data already available and the model predictions compared to experimental results.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

(1) ECT predictions based on the FPL differed significantly from experimental results in a number of comparisons wherein the liner or medium density was changed.

(2) Some part of the FPL model prediction errors may have been caused by the compressive load-deformation test used (Weyerhaeuser lateral support test). This will be checked.

(3) In addition to test difficulties there is evidence to suggest that the FPL model may not accurately handle local buckling phenomena.

(4) STFI sum models were better related to ECT changes due to densification than ring crush, particularly for the densified mediums.

(5) The simple sum models were less satisfactory for boards made with low weight densified liners.

PROJECT TITLE: Analysis of Board Structures	Date: 3/18/83
PROJECT STAFF: R. A. Halcomb/Open Position	Budget: $100,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use.	Period Ends: 6/30/84
	Project No.: 3272
PROGRAM AREA: Improved converting processes and converted products.	Approved by VP-R:

PROGRAM GOAL:

Identify the critical parameters which describe converting and end-use performance.

PROJECT OBJECTIVE:

- To develop the relationships between container performance and critical combined board properties and between combined board properties and component properties.
- The short term ('83-'84) goal is to use combined board ECT models based on local buckling of the components to assess impact of densification and other papermaking factors on ECT strength.

PROJECT RATIONALE:

Corrugated container sales account for over $6 billion in business and over 25% of all the paper tonnage produced in the U.S. Despite the importance of this business sector, corrugated containers have never been subjected to a rigorous structural analysis and accurate materials models for corrugating components have never been developed. It is not possible to accurately predict the properties of combined board and hence of a container.

The proposed Rule 41 changes will specify the ECT strength of combined board and hence will affect mill quality specifications. ECT is primarily dependent on the compressive strength of the components, which, in turn, are dependent on the in-plane and out-of-plane elastic stiffnesses of the liners and medium. Complete buckling models have been developed to treat this case but the results are difficult to use and interpret. It should be possible to develop modified relations incorporating the appropriate elastic stiffnesses which enter into our compressive strength model. This would enable us to use our developing knowledge on how papermaking factors affect the elastic stiffnesses to assess their impact on ECT strength. Such information would help guide our current work on compressive strength improvement.

RESULTS TO DATE:

Used Rayleigh-Ritz method for predicting failure loads in seven important load cases, and obtained experimental data to support these. Developed finite element model for MD beam-shaped combined board model. Developed understanding of scoreline effects on tube/box performance.

PLANNED ACTIVITY FOR THE PERIOD:

Local buckling ECT models will be analyzed to determine the best ways to simplify and incorporate the basic elastic properties of the components. We will then map the ECT response to practical changes in the critical parameters.

Specifically, we plan to:
- Relate ECT strength to the in-plane and out-of-plane elastic stiffnesses using our compressive strength model and allowing for local buckling effects.
- Determine the importance of local buckling effects on ECT.
- Use information on how papermaking factors affect the elastic stiffnesses to assess that impact on combined board ECT.

POTENTIAL FUTURE ACTIVITIES:

Application of similar techniques to end-use failures involving flexure and in-plane shear.

Status Report

ANALYSIS OF BOARD STRUCTURES

Project 3272

INTRODUCTION

This project is directed to the development of relationships between container, combined board and component properties. Because of the importance of compressive strength to container performance our initial work has focused attention on relationships between combined board edgewise compressive strength and the properties of the components. A sound understanding of this relationship will help us assess the impact of densification and other papermaking factors on compressive strength.

ECT is primarily dependent on the edgewise compressive strength of the components. This was established in past work at the Institute and more recently in work for the FKBG/FBA Ad Hoc Rule 41 Committee (1,2) where the sum of the component strengths was shown to be fairly well related to ECT. (These are termed sum models in later pages.) From this viewpoint papermaking factors which increase the compressive strength of liner and medium will increase combined board ECT.

However, corrugated board is a structure comprised of narrow plates of liner between flute tips and a series of curved plates of medium (Fig. 1). These plates may become unstable and buckle for boards made with lighter weight components. If local buckling occurs, the combined board ECT should be dependent on the edgewise compressive, modulus and thickness characteristics of the liner and medium. Thus papermaking factors which increase density might not increase ECT in the expected way if local buckling were important.

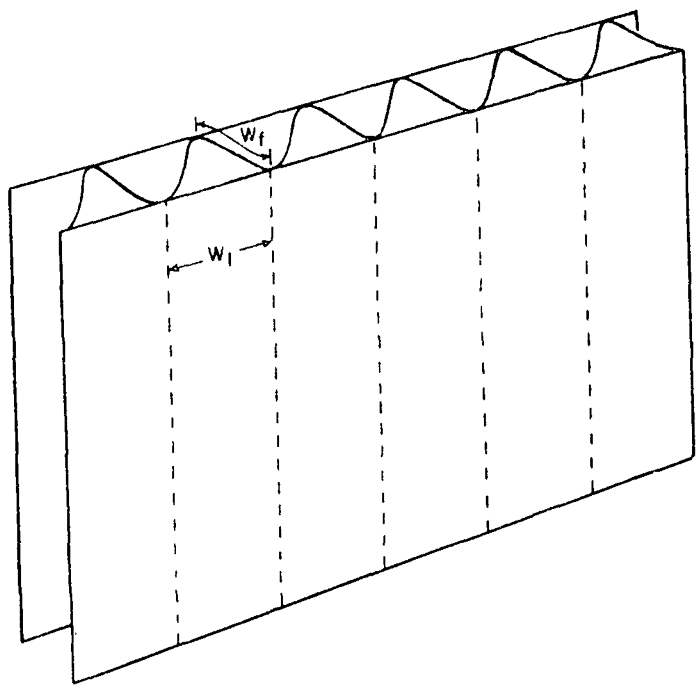

Figure 1. Corrugated board showing miniature liner and medium plate elements.

An approximate analysis carried out at the Institute (1) indicates that increasing density will increase ECT oven when allowance is made for buckling of the component elements (Fig. 2). Increasing density increases the component contribution whether buckling occurs or not, but the effect is less if buckling is a factor. The difference between the curves in Fig. 2 would be expected to vary with component basis weight -- being greater for lower liner weights.

Recent efforts to analyze combined board ECT strength in terms of local buckling have been made by Koning (3) and Johnson, et al. (4). The more recent model by Johnson at the Forest Products Laboratory (FPL) treats the problem as a case of inelastic buckling and assumes the components are isotropic. The solutions are non-linear and require empirically-fitted CD stress-strain curves. The extensive experimental and analysis time required to obtain these stress-

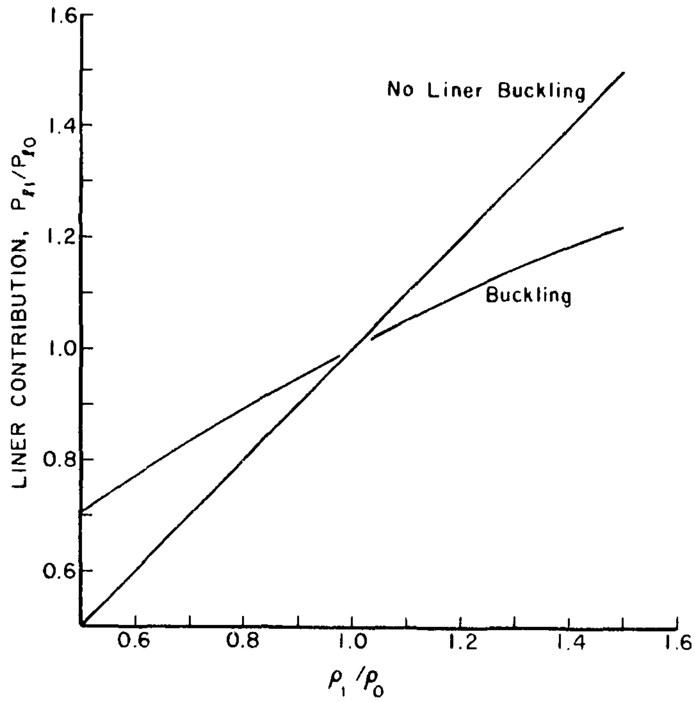

Figure 2. Estimated effects of density on the liner (or medium) contribution to combined board ECT strength (subscripts 1 or 0 denote the strength and density at a condition 1 relative to a reference condition 0).

strain curves make the FPL model in its present state of development difficult to use to estimate the effects of papermaking factors on ECT strength.

Our work is being directed to establishing which ECT models are most appropriate for further consideration. In this connection we know that the compressive strength of liner and medium are well related to the in-plane and out-of-plane elastic stiffnesses. It should be possible to incorporate the appropriate elastic stiffnesses in the ECT models. This would enable us to use our developing knowledge on how papermaking factors affect the elastic stiffnesses to assess their impact on ECT strength. Such information would help guide our current work on compressive strength improvement.

Our present work is directed to (1) exploring the use of the FPL model for combined board combinations where major changes have been made in component characteristics and (2) comparing the FPL and sum model predictions with the experimental results. Several phases of the work are discussed in the following text.

The FPL Model

The FPL model was developed in the late 1970's by M. W. Johnson, Jr., T. J. Urbanik and W. E. Denniston (4). It consists of a theoretical structural analysis of combined board and a computer algorithm for doing numerical computations. The model predicts compressive strength values for balanced single wall combined board based upon information about the flute geometry and the individual components. The current model assumes that materials are isotropic but the developers are working on a more advanced and simpler model which makes use of the components' orthotropic nature.

The FPL model uses the input data for the flute geometry and the component characteristics to determine (1) the strain at which failure of the combined board occurs, (2) which of two possible modes of failure, local buckling or compressive failure, initiates the combined board failure and (3) in which of the two components, liner or the medium, the failure is initiated. Using this strain, the stresses in each elements are obtained from the stress-strain formulas whose parameters are supplied as part of the input data. The ECT strength is then calculated from these stresses. The FPL model's predictions for ECT are thus sensitive to the individual component's stress-strain curves. These curves are in turn dependent upon the particular load deformation apparatus with which they are obtained. All FPL model predictions cited in this report are based upon component stress-strain information obtained using a

Weyerhaeuser lateral support compression device (WLS). For this reason all FPL model predictions in this report are identified as FPL-WLS predictions.

Experimental Data

The experimental data upon which this report is based consists of 17 balanced C-flute combined boards. These boards were made from ten mediums and ten liners, having various properties.

Table I shows the seventeen combined board lettered A through Q and divided into five groups for analysis purposes. For each board the table indicates the source for the liner and medium (C for commercial and E for IPC experimental), the liner and medium basis weight, liner and medium IPC apparent density and combined board experimental ECT.

Experimental Results vs. FPL-WEY Predictions

The four combined boards in Group 1 in Table I were made to test the effects of component orientation. The same liner and medium were used in boards A and B but while the medium in A had the conventional machine/cross-machine orientation for combined board, the medium in board B was fluted and installed at right angles to the conventional orientation. Similarly the same liner and medium were used in making boards C and D but while the liners in board C had the conventional orientation, the liners in D were installed at right angles to the conventional orientation. While these orientations are unfeasable for commercially produced board, it was thought that these usual assemblages might prove helpful in evaluating model ECT predictions versus experimental ECT results. Figure 3 shows the experimental ECT's (the horizontal axis) versus the FPL-WLS predicted ECT's (the vertical axis) for Group 1. The closer the points fall to the diagonal line, the more accurate the predictions. The FPL-WLS

TABLE I

EXPERIMENTAL COMBINED BOARDS

	Board	Liner Source	Medium Source	Liner BW (g/m^2)	Medium BW (g/m^2)	Liner Density (kg/m^3)	Medium Density (kg/m^3)	Experimental ECT (lb/in)
Group 1	A	C*	C*	205.0	130.3	707	687	44.6
	B	C	C	205.0	130.3	707	687	55.6
	C	C	C	208.9	127.9	779	659	40.9
	D	C	C	208.9	127.9	779	659	55.0
Group 2	E	C	E	208.5	198.9	714	533	48.2
	F	C	E	208.5	197.7	714	764	59.8
	G	C	E	208.5	201.3	714	856	64.1
	H	C	E	208.5	200.8	714	1,018	69.6
Group 3	I	C	E	201.6	127.3	700	484	40.0
	J	C	E	201.6	125.3	700	804	46.9
	K	C	E	201.6	126.5	700	900	49.5
Group 4	L	E	C	197.0	124.7	455	636	41.4
	M	E	C	200.9	124.7	716	636	48.2
	N	E	C	199.0	124.7	838	636	51.1
Group 5	O	E	C	162.5	124.7	453	636	35.6
	P	E	C	164.7	124.7	742	636	36.6
	Q	E	C	162.0	124.7	848	636	38.6

*C indicates commercial component
E indicates IPC experimental component

predictions for boards A, B, and C were close to the observed results but the prediction was not so close for board D. The model's prediction was 63.4 lb/in while the observed ECT was 55.0 lb/in.

In order to make relative comparisons between predicted and experimental values we define the relative percent error (r.p.e.) as:

$$r.p.e. = \frac{(\text{Predicted - Experimental}) * 100}{\text{Experimental}}$$

The r.p.e.'s for the boards A, B, C and D were respectively -6%, -1%, -5%, and 15%.

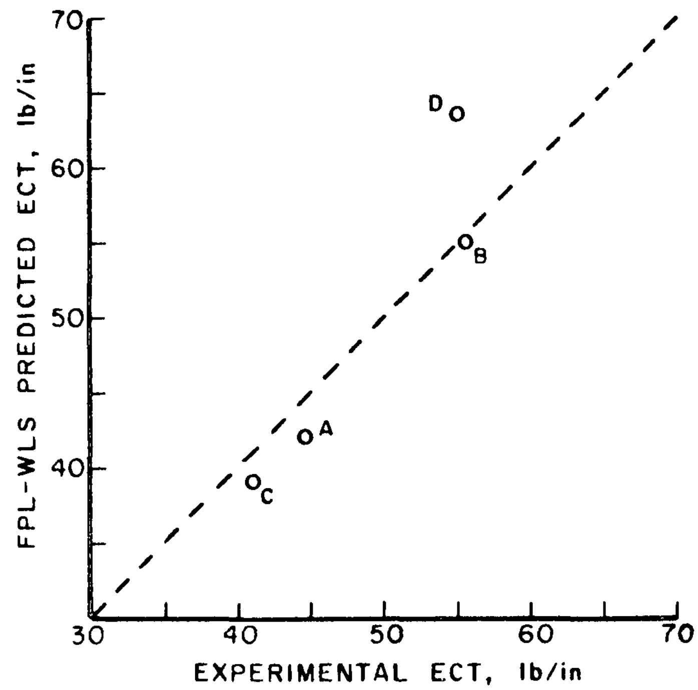

Figure 3. Effect of normal and reverse machine orientation. [(A) normal medium, (B) reversed medium orientation; (C) normal liners, (D) reversed liner orientations.]

The four boards in Group 2 were made using a single pair of commercial liners together with 4 different experimental mediums having approximately the same basis weight, 200 g/m^2, but each having a different density.

The three boards in Group 3 were made from a single pair of commercial liners together with three different experimental mediums having approximately the same basis weight, 126 g/m^2, but with different densities. Figure 4 shows the FPL-WLS predictions for ECT versus the experimentally observed ECT's for the boards in Groups 2 and 3. The r.p.e.'s for the boards E, F, G, and H in the heavier medium basis weight group were 11%, -4%, -8%, and -12% respectively. While the FPL-WLS model correctly predicted an increase in ECT with increasing medium density for this group, the overall increase was underpredicted. The model's mode of failure for each of these four boards was compressive failure of the liner, that is the model predicted that the ultimate compressive strength of the liner was reached before any local buckling could occur. The r.p.e.'s for boards I, J, and K in the lower medium basis weight group were 8%, -14%, and -25% respectively. The plot of predicted versus experimental ECT's in Fig. 4 for the 126 g/m^2 mediums form a different pattern than that for the heavier basis weight mediums. The model predicted decreases in the combined board ECT with increasing medium density for the 126 g/m^2 mediums while the experimental results showed an increase in ECT with increasing medium density. The model's mode of failure for Board I was the same as that for the previous heavier basis weight group, namely, compressive failure of the liner. The mode of failure for boards J and K according to the model was local buckling of the medium. This point will be discussed shortly.

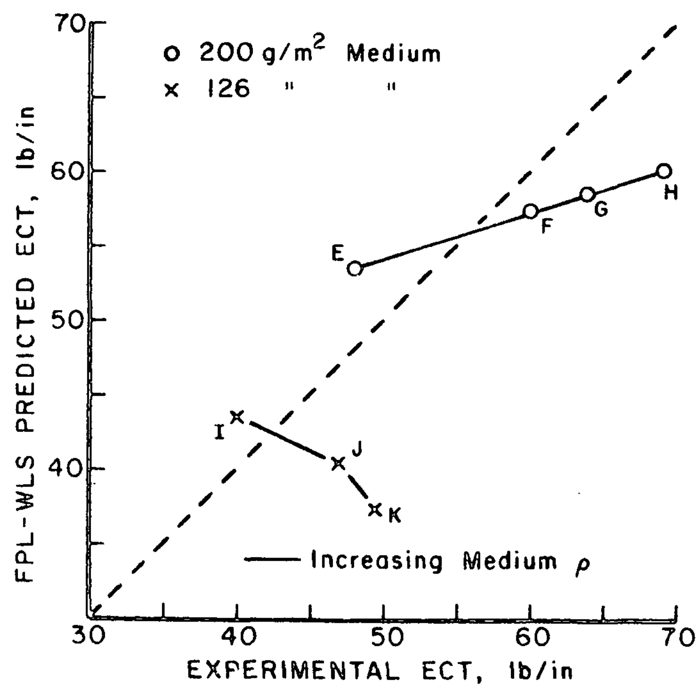

Figure 4. FPL-WLS predictions for boards made with medium of varying density.

The three boards in Group 4 were made using a single commercial medium together with three different pairs experimental liners having approximately the same basis weight, 200 g/m^2, but with different densities. The three boards in Group 5 were made using a single commercial medium together with three different pairs experimental liners having approximately the same basis weight, 162 g/m^2, but with different densities. Figure 5 shows the FPL-WLS predictions versus the experimental ECT's for the boards in Groups 4 and 5. The r.p.e.'s for the higher basis weight boards L, M, and N were -1%, -2%, and -17% respectively. The FPL-WLS predictions for boards L and M are very accurate but the model noticeably underpredicted the ECT for board N. The model's modes of failure for L and M were compressive failure of the medium and compressive failure of the liner respectively. Local buckling of the liner was the mode of failure for board N. The r.p.e.'s for the three light basis weight boards, O, P, and Q were respectively -1%, -10%, and -23%. The FPL-WLS predictions decreased with increasing liner density while the experimental results showed small increases in ECT with increasing liner density. The mode of failure for board O was compressive failure of the medium and the mode for P and Q was local buckling of the liner.

Considering all 17 combined boards, the FPL model using the WLS test data underpredicted the experimentally observed ECT's in 14 out of 17 cases and overpredicted in the remaining three cases. The average r.p.e. for the 14 underpredicted cases was -9% while the average r.p.e. for the three overpredicted cases was 12%.

The predominance of low predictions could be attributed to the FPL model itself, the WLS test data or an interaction of the two. It appears that at least part of the problem is related to using WLS test data. The maximum FPL

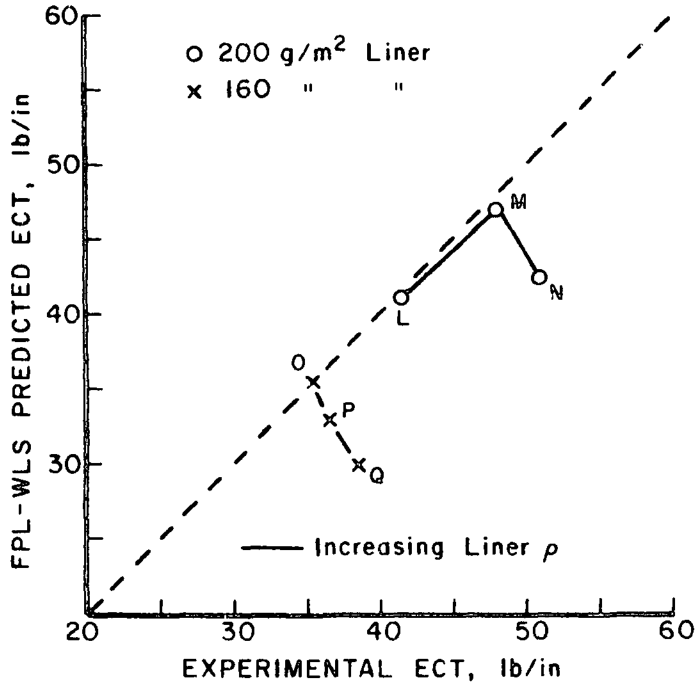

Figure 5. FPL-WLS predictions for boards made with liners of varying density.

model prediction is limited by the sum of the ultimate stresses for each of the three components taken over the appropriate cross sectional areas. By examining these maximum values it appears that the WLS tester may not be the most suitable compression test device to use in conjunction with the FPL model. The Institute and the Forest Products Laboratory are currently working out arrangements to have samples of some of the components for this study tested using FPL's vacuum uniaxial compression tester. These new stress-strain parameters are expected to improve the FPL model's predictions over those cited in this report.

However, the FPL model may have some deficiencies, particularly when it predicts a local buckling mode of failure (e.g. boards J, K, N, P and Q). It is possible to calculate what the FPL-WLS predictions for ECT would have been for these five boards if the mode of failure were compressive failure of the weakest components instead of local buckling. Below are two columns of r.p.e.'s for these five boards. The first column consists of the r.p.e.'s already quoted in this report and calculated from the FPL-WLS's predictions based upon local buckling as the mode of failure. The second column gives what the r.p.e.'s would have been if the mode of failure had been compressive failure instead.

Board	R.P.E. based on actual FPL-WLS Predictions	R.P.E. based on possible FPL-WLS Predictions
J	-14	-2
K	-25	-6
N	-17	2
P	-10	18
Q	-23	14

For four of the five boards, all except board P, the absolute value of the second r.p.e. is noticeably smaller than the absolute value of the first. This is an indication that the model is not handling the local buckling phenomena as well as might be desired. It is not clear what part of this problem may be interlinked with the problem of using WLS test data. This mode of failure issue will be addressed again if it persists with the new FPL stress-strain test data.

Simple Sum and FPL-WEY Predictions versus Experimental ECT

As stated in the introduction, previous work has shown that there is a fairly strong relationships between the sum of the component CD strengths and the combined board ECT, at least for commercial boards. In this section models based upon simple sum predictions using the formula:

Sum = 2. X Liner CD Strength + Draw Factor X Medium CD Strength

and using either ring crush or STFI component data are compared with the FPL-WLS predictions. These comparisons were made by plotting the percent changes in ECT as a function of the density of the mediums for Groups 2 and 3 and as a function of the density of the liners for Groups 4 and 5. The percent changes in ECT have been calculated using the first board in each group as the standard for that group.

With respect to Group 2 the percent increase experimental ECT in going from board E with the least dense medium to board H with the most dense medium was 44% as can be seen in Fig. 6. For the same two boards the STFI sum model predicted a 26% increase. The ring crush sum model and the FPL-WLS predictions showed smaller percent improvements for these boards. The figure illustrates that for this heavy weight medium group the three models consistently underestimated the percent improvement that was experimentally observed. The STFI sum model came the closest to the experimental results with the FPL-WLS model and ring crush sum model being second and third. Figure 7 shows that all three model also underestimated the experimental ECT improvement obtained by medium densification for the lighter weight mediums. At the highest medium density the experimental percent increase in ECT was 23% while the STFI sum model predicted a 16% increase, the ring crush sum model predicted a 6% improvement and FPL-WLS predictions showed decreases.

Figure 8 shows that the maximum percent increase in experimental ECT obtained using densified liners (200 g/m^2) was 23%, while the STFI sum model predicted a 37% improvement and the ring crush sum model predicted a 38% improvement. The FPL-WLS model predicted the initial improvement via densification

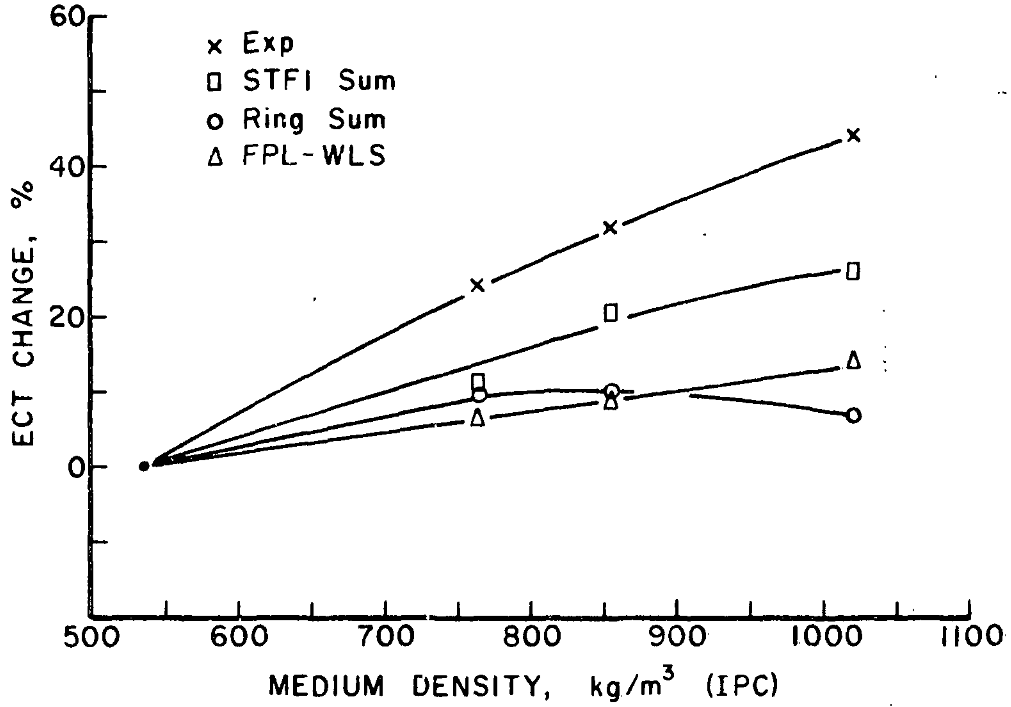

Figure 6. Comparison of % ECT changes for boards made with 200 g/m² mediums of varying density.

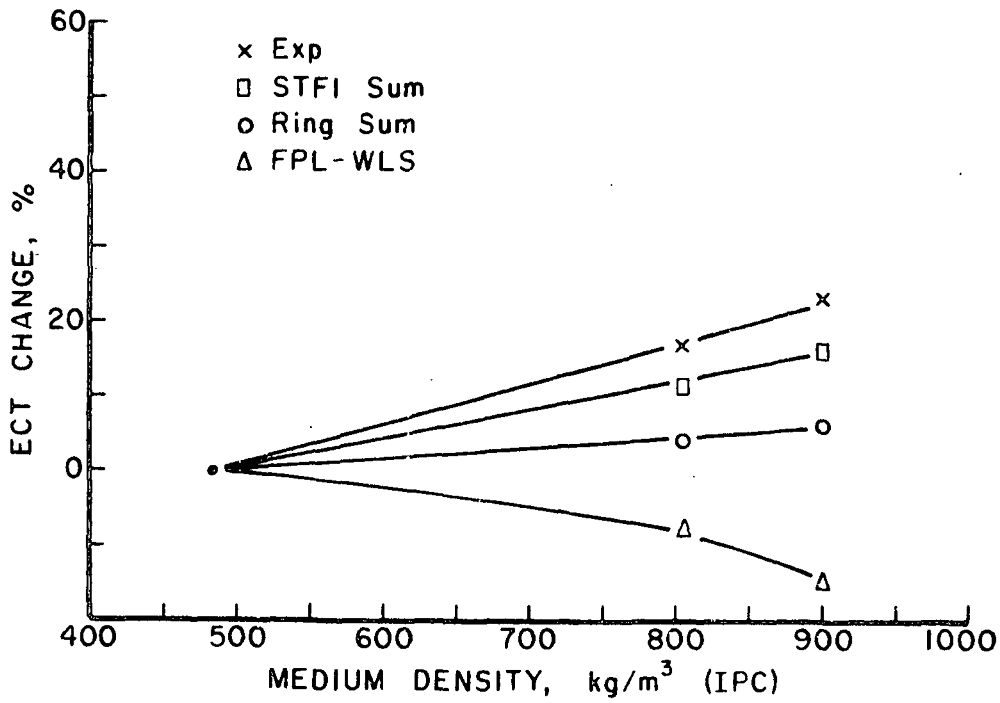

Figure 7. Comparison of % ECT changes for boards made with 126 g/m² mediums of varying density.

more accurately than either of the sum models but then its accuracy at the highest liner density fell off appreciably. The percent increase in experimental ECT for the lighter weight liner group was 8% in going from board O to board Q as illustrated in Figure 9. The STFI sum model predicted a 41% improvement for board Q over board O and the ring crush sum model predicted a 38% improvement for the same boards. As discussed earlier, the FPL-WLS model predicted decreases in ECT in going from board O to board Q.

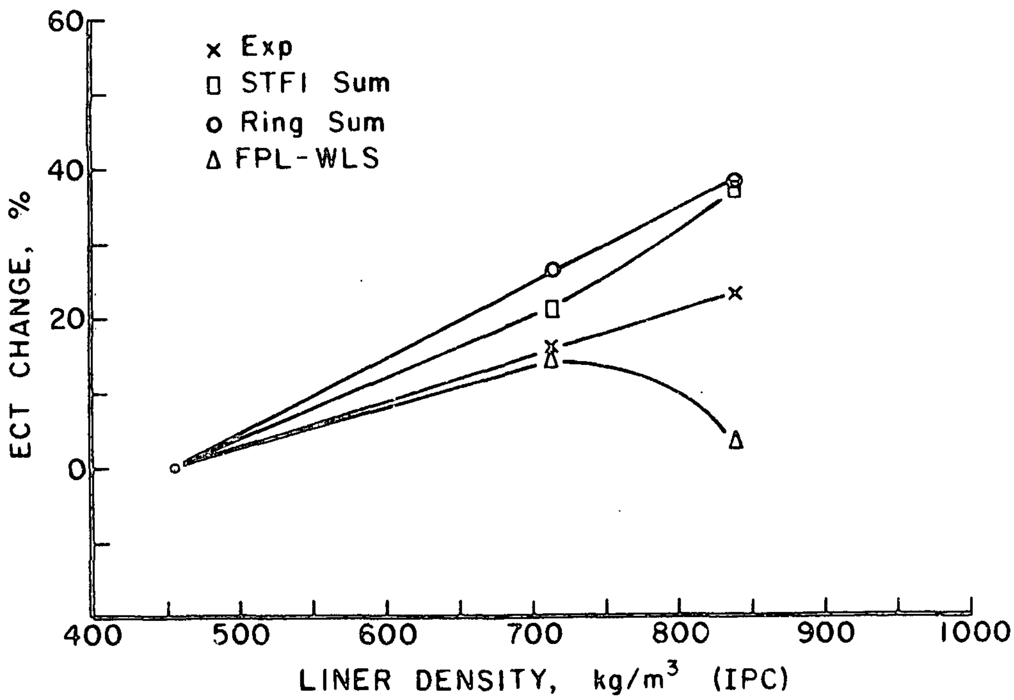

Figure 8. Comparison of % ECT changes for boards made with 200 g/m^2 liners of varying density.

Possible trouble sources in the FPL-WLS model were discussed in the previous section. With respect to the ring crush sum model, it becomes apparent by reviewing Figs. 6, 7, 8, and 9 that overall, this sum model predicts the percent improvements less accurately than the STFI sum model. As for the STFI sum model, it underpredicts the ECT improvement for Groups 2 and 3 with the densified

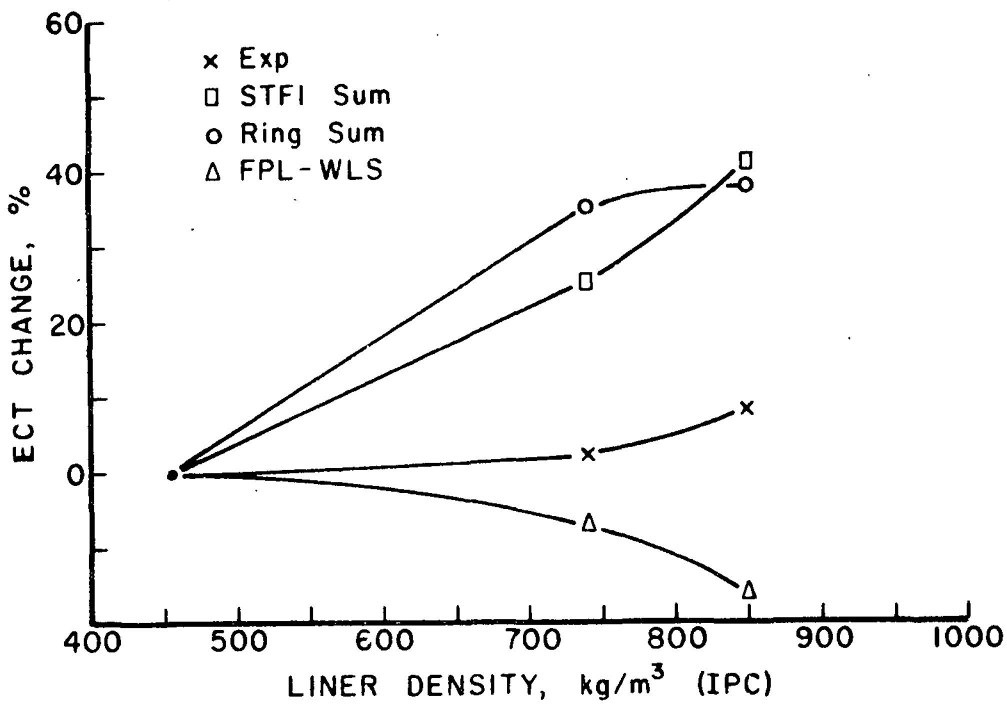

Figure 9. Comparison of % ECT changes for board made with 160 g/m^2 liners of varying density.

mediums and significantly overpredicts the ECT improvement for Groups 4 and 5 with the densified liners. This information would suggest, as is discussed in the report for Project 3469, that the liner and medium act in somewhat different ways with respect to their contribution to the edgewise strength of the combined board. This may be due in part to the curved nature of the medium in the sandwich construction as compared to the flat plate type contribution of the liners. This contribution difference between the liner and the medium may help explain some of the difficulties the FPL model experienced since it divides both the liner and the medium up for analysis purposes into flat plates.

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

Status Report

to the

PAPER PROPERTIES AND USES

PROJECT ADVISORY COMMITTEE

Project 3472

RHEOLOGY AND APPLICATION OF COATINGS AND ADHESIVES

February 10, 1984

PROJECT SUMMARY: (July 1, 1983-June 30, 1984)	Date: Feb. 16, 1984
PROJECT TITLE: RHEOLOGY AND APPLICATION OF COATINGS AND ADHESIVES	Budget: $50,000
	Period Ends: 6/30/84
PROJECT STAFF: Open	Project No: 3472

PROGRAM GOAL: Identify the critical parmaeters which describe converting and end-use performance.

PROJECT OBJECTIVE:

To determine and quantify the factors that control the transfer of an adhesive from an applicator roll to a medium flute tip.

PROJECT RATIONALE, PREVIOUS ACTIVITY, and PLANNED ACTIVITY FOR FISCAL 1983-84 are on the attached 1983-84 Project Form.

SUMMARY OF RESULTS THIS PERIOD: (October 1983 - March 1984)

Because of manpower shortages, there has been no activity on this project.

PROJECT TITLE: Adhesive Transfer	Date: 3/31/83
PROJECT STAFF: Open	Budget: $50,000
PRIMARY AREA OF INDUSTRY NEED: Properties related to end use.	Period Ends: 6/30/84
	Project No: 3472
PROGRAM AREA: Improved converting processes and converted products.	Approved by VP-R: JW

PROGRAM GOAL: Identify the critical parameters which describe converting and end use performance.

PROJECT OBJECTIVE:

To determine and quantify the factors that control the transfer of an adhesive from an applicator roll to a medium flute tip.

PROJECT RATIONALE:

Adhesives must be applied in precisely metered amounts in high speed processes such as corrugating. The fundamental understanding of this transfer process is not sufficient to permit the effective design of applicator systems nor to control the pertinent rheological characteristics of the applied material. The net result is that systems in use are decidedly suboptimal thus contributing to speed limitations, excess materials costs, and overall poor performance.

RESULTS TO DATE:

The pertinent literature has been reviewed, the key variables and relationships have been identified and a preliminary experimental approach has been formulated. Construction of apparatus and some experimental work will be completed in this fiscal year.

PLANNED ACTIVITY FOR THE PERIOD:

Complete the development of the experimental apparatus and the collection of data for the various cases of interest. Develop the required descriptive relationship and confirm with laboratory application equipment.

POTENTIAL FUTURE ACTIVITIES:

Consider the development of improved application concepts based on the results of this work.