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SINGLE-FACER GREEN BOND STRENGTH

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Executive Summary.

The quality of the bonds between the linerboard facings and the fluted medium is a critical factor in the performance of boxes made from the corrugated board. The development of the single-facer green bond strength under actual corrugating conditions was measured as a function of the bonding time, the level of preconditioning of the linerboard and medium, and the physical properties of the linerboard and medium, within 18 to 150 milliseconds of its formation at the pressure nip.

It was found that the green bond strength development can be characterized by an Induction Time, during which no measurable bond strength occurred, followed by an increase in bond strength, Bonding Rate, that is linear with time. This observation suggests that the green bond is formed primarily by the increase in the viscosity and tack of the adhesive. Increased preconditioning improved the rate of the green bond strength development through reducing the Induction Time and increasing the Bonding Rate. The results suggest that the preconditioning at the single-facer should be increased simultaneously with the increase in corrugator speed in order to minimize the probability of weak bonds or bonding defects.

A barrier at 30 milliseconds for the calculated time to 100% bond was observed. A more porous and less wettable medium and a smoother wire side of the linerboard improved the Bonding Rate. Increased preconditioning also improved the cured Pin Adhesion, Flat Crush, and Edge Crush Test of the combined board.

Key Words

Corrugating, Bonding, Single-facer, Preconditioning, Medium Properties, Linerboard Properties, Combined Board Properties

Abstract

The development of the single-facer green bond strength under actual corrugating conditions was measured as a function of the bonding time, the level of preconditioning of the linerboard and medium, and the physical properties of the linerboard and medium, within 18 to 150 milliseconds of its formation at the pressure nip.

The green bond strength development can be characterized by an Induction Time, during which no measurable bond strength occurred, followed by an increase in bond strength, Bonding Rate, that is linear with time. This observation suggests that the green bond is formed primarily by the increase in the viscosity and tack of the adhesive. The green bond strength is improved by increased preconditioning, a more porous and less wettable medium, and a smoother wire side of the linerboard.

Introduction.

The quality of the bonds between the linerboard facings and the fluted medium is a critical factor in the performance of boxes made from the corrugated board. A weak bond strength or defects such as blisters or loose edges adversely affect the functional box performance and the box plant waste costs.

The bond on a corrugator is achieved with an aqueous base starch adhesive that is applied to the tips of the fluted medium. The linerboard material is brought into contact with the adhesive coated flute tip; and pressure, heat, and time are used to set the starch adhesive and to form the bond.

There are two types of bonds formed on the corrugator, the single-face bond and the double-face bond. The double-face bond is formed

by sandwiching the corrugated structure between a steam heated hot plate and a moving belt that is held down by steel rollers or air pressure. This provides continuous heat and pressure until the double-backer bond has developed sufficient strength to hold the plies together. The single-facer bond, on the other hand, is formed by applying heat and pressure to the bonding site at a nip between the lower corrugating roll and the pressure roll in the single-facer. The bond exiting this nip must be of sufficient strength to hold the web together until the final cured bond is achieved. This initial bond at the single-facer is called the "green bond."
The single-face bond can not be reformed in subsequent stages on the corrugator if the green bond separates due to mechanical stresses.

Studies have shown that the formation of the single-face bond is a complex process that is affected by the paper and adhesive properties and by the corrugator process factors of heat, moisture, pressure, and speed, (1, 2, 3). The corrugator bonding process has been characterized by four major steps, the application of the adhesive, the wetting of the substrates by the adhesive, the penetration of the adhesive into the substrates, and the setting of the adhesive to form the bond. It has been shown that the setting of the adhesive occurs through an increase in the viscosity and tack of the adhesive and by the subsequent removal of water from the glueline area, (2, 4, 5, 6).

Microscopic examination of the single-face bond area has shown four distinct areas in the bond with different bonding potential. The final, cured bond strength has been associated with the adhesive fillets on the flanks of the flute tip, (5, 7). The bond area at the point of the pressure nip has a low dry bond strength but is thought to provide immediate adhesion, (2, 5, 7). These various bond areas have been shown to contain differing proportions of gelled and nongelled starch granules, varying locations and structures of the starch macromolecules, and various degrees and mechanisms for the starch penetration into the two substrates, (2, 5, 7, 8, 9). Studies have also been published that have related the cured bond strength to the paper properties, the adhesive properties, and to the corrugator process factors, (1, 2, 3, 10, 11). The development of the bond strength with time has also been reported under noncorrugating conditions, (4, 5, 6).

In this study, the development of the single-facer green bond strength under actual corrugating conditions was measured as a function of the bonding time, the level of preconditioning of the linerboard and medium, and the physical properties of the linerboard and medium.

Experimental Methods.

All of the single-facer green bond experiments were done on the

IPST 14-inch wide pilot single-facer and pilot double-backer. The paperboard used in the study consisted of 15 commercial 26 lb/msf medium materials and 22 commercial 42 lb/msf linerboard materials from different producing mills. The corrugating adhesive was the standard formulation used by IPST for high-speed corrugating trials.

The strength of the single-face green bond was determined by the use of a wedge devise which was located on the exit side of the nip formed by the lower corrugating roll and the pressure roll, Figure 1. The medium used in the study was two inches wider than the linerboard, which allowed the linerboard web to pass between the wedge edges with no mechanical force being applied. The edges of medium, however, were contacted by the wedge and experienced an upward force due to the contour of the wedge edges. This upward force provided a stress on the green bond that could result in a separation of the fluted medium from the linerboard if the green bond was weak. The strength of the green bond determined the extent of the bond separation. A strong green bond resulted in no separation of the gluelines, while a weaker green bond resulted in varying degrees of debonding extending toward the center of the single-faced web up to the point of complete delamination of the linerboard from the medium. The amount of delamination was measured and used as a gage of the green bond strength.

The wedge tip was located three inches from the centerline of the nip between the lower corrugating roll and the pressure roll. Each of the trial materials was run at corrugator speeds ranging from 100 fpm to 800 fpm in 100 fpm intervals or to the fastest speed at which 100% delamination occurred. Since the wedge position was fixed, the corrugator speed determined the bonding time allowed before the wedge debonding force was applied. This bonding time varied from 150 milliseconds at 100 fpm to 18.75 milliseconds at 800 fpm.

Two levels of preconditioning of the medium and linerboard were used. The more preheat condition represents the normal operating mode for the IPST pilot single-facer. The less preheat condition represents a subnormal operating mode. A constant medium material with normal preconditioning was used for the linerboard experiments, and a constant linerboard material with normal preconditioning was used for the medium experiments. The change in corrugator speed also affected the degree of preconditioning achieved since the wraps and steam flows were held constant for each of the two preconditioning levels. Therefore, the experimental design used does not allow a complete separation of the effect of bonding time and preconditioning on the bond strength development.

Green Bond Strength Analysis.

The experimental data for the average of all medium samples and all linerboard samples are shown in Figure 2, where the percent bonded area is plotted against the bonding time. The curves for the normal and the subnormal preconditioning levels are shown separately. The shape of these curves is similar to those reported by Whitsitt, et al. for the formation of the double-backer bond, (12).

All four curves show a finite Induction Time within which no bonding was observed, followed by a linear increase in bonded area which is defined as the Bonding Rate. This linear increase in bonding continued up to the maximum bond strength observed with the exception of the medium study where normal preconditioning was used. This curve showed a pronounced reduced slope shoulder in the 30 to 70 millisecond bonding time region. There is no explanation for this anomaly at this time. The fact that none of these average curves achieved a 100% bond is believed to be due to a combination of the mechanical action of the wedge and the lack of significant water migration away from the bond area within the 150 millisecond maximum bonding time used in this study. The data show the positive effect of more preconditioning on the total rate of bond development. The slight drop-off in bonding for the linerboard can be attributed to overheating at slower corrugator speeds which caused crystallization of the starch, (2).

The observed Induction Time and Bonding Rate values can be used to calculate a time to 100% bonding, Equation 1.

$$100\%\ \text{Bond Time} = \text{Induction Time} + \frac{100}{\text{Bonding Rate}} \qquad (1)$$

The measured and calculated bond development parameters for each of the four conditions are summarized in Table I. The data for each of the 22 linerboard materials and 15 medium materials are shown in Figures 3 and 4, respectively. More preconditioning of the linerboard reduced the calculated time to 100% bond by an average of 12.0 milliseconds or 25.6%, Table I. The comparable values for the medium were 30.5 milliseconds or 41.1%. For the linerboard, 31% of the improvement was due to a reduced Induction Time and 69% to an increased Bonding Rate. For the medium, 48% of the improvement was due to a reduced Induction Time and 52% to an increased Bonding Rate. The data indicate that added preconditioning of linerboard improves the green bond strength predominantly by increasing the Bonding Rate and secondarily by reducing the Induction Time. The improvement in green bond strength development in medium with added preconditioning is about equally divided between the two effects. Changes in the preconditioning of the medium has more of an effect on the green bond strength development than does changes to the preconditioning of the linerboard; although, both are important.

Figures 3 and 4 show that increased preconditioning tends to equalize the rate of green bond strength development as influenced by material properties. The data also show that no material achieved a time to 100% bond of less than 30 milliseconds. This apparent time barrier at 30 milliseconds is demonstrated best by the linerboard data in Figure 3. Linerboard samples LN and LC had calculated time to 100% bond values of 30 to 35 milliseconds with subnormal preconditioning. When normal preconditioning was used, virtually no improvement in bonding time occurred. In comparison, linerboard samples LF, LG, LJ, and LE had bonding times ranging from 40 to 60 milliseconds when subnormal preconditioning was used. The bonding time of these samples improved to 30 milliseconds when normal preconditioning was used. It is hypothesized that this 30 millisecond barrier is a result of the total process, i.e., the adhesive, the preheating capacity, and the materials. Additional work would be needed to determine whether this barrier could be overcome so as to improve the green bond strength development and to determine which of the process variables has the most impact.

Previous researchers have hypothesized that the initial green bond is produced by the forced penetration and dehydration of the adhesive along the pressure line of the single-facer, (2, 5, 7). The adhesive that is present in the fillet region of the flute flank becomes gelatinized by the latent heat, starts to penetrate the paperboard, and increases in viscosity and tack to further increase the green bond strength, (4, 6). Subsequent water migration from the bond area further strengthens the bond until the fully cured bond is achieved, (5, 7). Unlike water, the absorption of a starch adhesive slurry into paperboard has been shown to lack of a measurable, finite wetting time, and absorption is expected to occur simultaneously with contact, (5). These studies were based on microscopic examination of the bond site, physical testing of cured bonds, or by experiments conducted under noncorrugating conditions.

The results of this study suggest that any pressure nip bond that exists is extremely weak immediately after exiting the nip. If this was not the case, the bond curves shown in Figure 2 would not have exhibited a measurable Induction Time. With normal preconditioning of the paperboard, a measurable green bond begins to form, on average, after 19 to 20 milliseconds after exiting the pressure nip and continues to increase linearly with time. This type of behavior is more consistent with the adhesive viscosity increase and subsequent moisture migration from the glueline as the main mechanisms for the development of the green bond. The observed beneficial effect of increased preconditioning also supports this hypothesis.

Effect of Material Properties.

Statistical regression analyses of selected paper properties to the green bond Induction Time, Bonding Rate, and calculated time to 100% bond were performed. The regressions were done separately for the linerboard and the medium studies and for the two different preconditioning levels. The paper test properties included Gurley porosity, Bendtsen smoothness, hot friction, and various liquid absorption tests.

The only statistically significant correlations that were found, using the 95% probability level, involved either the Bonding Rate or the calculated time to 100% bond. In all cases, the statistical correlation probability was higher for the Bonding Rate than for the calculated time to 100% bond, indicating that the Bonding Rate was the controlling factor in the correlations.

The strongest correlation found for the medium study when normal preconditioning was used is shown in Equation 2. The Bonding Rate increases with a more porous and less wettable medium.

$$\text{BONDING RATE} = 0.0276(\text{WATER ABS.}) - 0.0866(\text{POR.}) + 5.22 \qquad (2)$$

R-SQUARED = 0.490 F-RATIO PROBABILITY = 99%

VARIABLE RANGE INFORMATION

Variable	Average	Minimum	Maximum
Bonding Rate, % Bond/m-sec.	4.54	2.22	7.00
Water Abs., T-819, sec.	32.4	3.6	97.2
Gurley Porosity, sec.	18.3	7.8	28.6

The strongest correlation for the medium study when subnormal preconditioning was used is shown in Equation 3. The Bonding Rate increases with a less porous medium. A definitive explanation is not available at this time as to why the effect of medium porosity differs depending on the level of preconditioning. However, it can be hypothesized that it may be due to the balance between the cooking rate of the starch at the flute tip and the rate of moisture migration away from the glueline.

$$\text{BONDING RATE} = 0.134(\text{POR.}) + 0.171 \qquad (3)$$

R-SQUARED = 0.410 F-RATIO PROBABILITY = 99%

VARIABLE RANGE INFORMATION

Variable	Average	Minimum	Maximum
Bonding Rate, % Bond/m-sec.	2.61	1.83	3.50
Gurley Porosity, sec.	18.3	7.8	28.6

The strongest correlation for the linerboard study with subnormal preconditioning is shown in Equation 4. The Bonding Rate increased with a smoother wire side linerboard surface. No statistically significant correlations were found between any of the bonding parameters and the linerboard properties when normal preconditioning levels were used.

RATE OF BOND = 8.59 - 0.00212(WIRE SIDE SMOOTH.) (4)

R-SQUARED = 0.209 F-RATIO PROBABILITY = 97%

VARIABLE RANGE INFORMATION

Variable	Average	Minimum	Maximum
Bonding Rate, % Bond/m-sec.	4.85	2.17	9.76
Bendtsen Smooth., Wire Side, sec.	1780	1158	2444

These results for the single-facer green bond are consistent with those reported for the double-backer bond development. A less wettable and less porous medium and a more porous, more wettable, and smoother wire side linerboard were reported to increase the rate of the double-backer bond strength development, (12).

The calculated Bonding Rates, using the above correlation equations, are shown plotted versus the measured Bonding Rates in Figure 5. As expected from the correlation coefficients, a closer agreement is observed for the medium material than for the linerboard. In both cases, it would appear that there are other variables involved that were not identified by this study.

The implications of the results are that the single-face web should be protected from mechanical forces for as long a time as possible. This would include minimizing vibration, variation in tensile force, flexing, and web flutter. Proper preconditioning is important to achieving the green bond strength. The various steaming and heating units on the single-facer need to be kept in proper working condition and with the proper temperatures and steam quality. The container board properties of porosity, water absorption, and smoothness can influence the green bond, especially at reduced preconditioning levels.

Many corrugators still operate with wide fluctuations in speed. It is a normal practice to reduce the preconditioning when the corrugator is slowed in order to minimize warp. This work indicates that care should be taken to simultaneously increase the preconditioning when the corrugator speed is again increased so as to maintain the green bond strength and thereby minimize the probability of generating blisters and other bonding defects.

Combined Board Properties.

The summary of the combined-board physical properties is given in Table II for both the medium and linerboard experiments and for both the normal preconditioning and subnormal preconditioning levels. The statistical analysis of the difference in TAPPI conditioned strength between normal and subnormal preconditioning shows that the Flat Crush, Pin Adhesion, and Edge Crush Test properties are higher, at the 95% or greater probability level when normal preconditioning was used. However, the magnitude of the improvement was relatively small, being between 2.5% and 8.5%.

Conclusions.

The data support the following conclusions concerning the development of the single-facer green bond strength within the 18 to 150 millisecond time after the pressure roll nip for the experimental technique used in this study.

1. The green bond strength development can be characterized by an Induction Time, during which no measurable bond strength occurred, followed by an increase in bond strength, Bonding Rate, that is linear with time.

2. This observation suggests that the green bond is formed primarily by the increase in the viscosity and tack of the adhesive and by the start of moisture migration away from the glueline. Any instantaneous pressure nip bond that exists is too weak to be measured by the techniques used.

3. Increased preconditioning improved the rate of the green bond strength development through reducing the Induction Time and increasing the Bonding Rate. For medium, the affect was due equally to the two mechanisms. For linerboard, the affect was due 2/3 to the increased Bonding Rate and 1/3 to the reduced

Induction Time.

4. A barrier at 30 milliseconds for the calculated time to 100% bond was observed for the process used in this experiment. Paperboard materials having a time to 100% bond of 30 milliseconds with reduced preconditioning did not exhibit an improvement when more preconditioning was used.

5. Paper properties were found that were correlated to the Bonding Rate. A more porous and less wettable medium and a smoother wire side of the linerboard improved the Bonding Rate.

6. Increased preconditioning improved the cured Pin Adhesion, Flat Crush, and Edge Crush Test of the combined board.

7. The results suggest that the preconditioning at the single-facer should be increased simultaneously with the increase in corrugator speed in order to minimize the probability of weak bonds or bonding defects.

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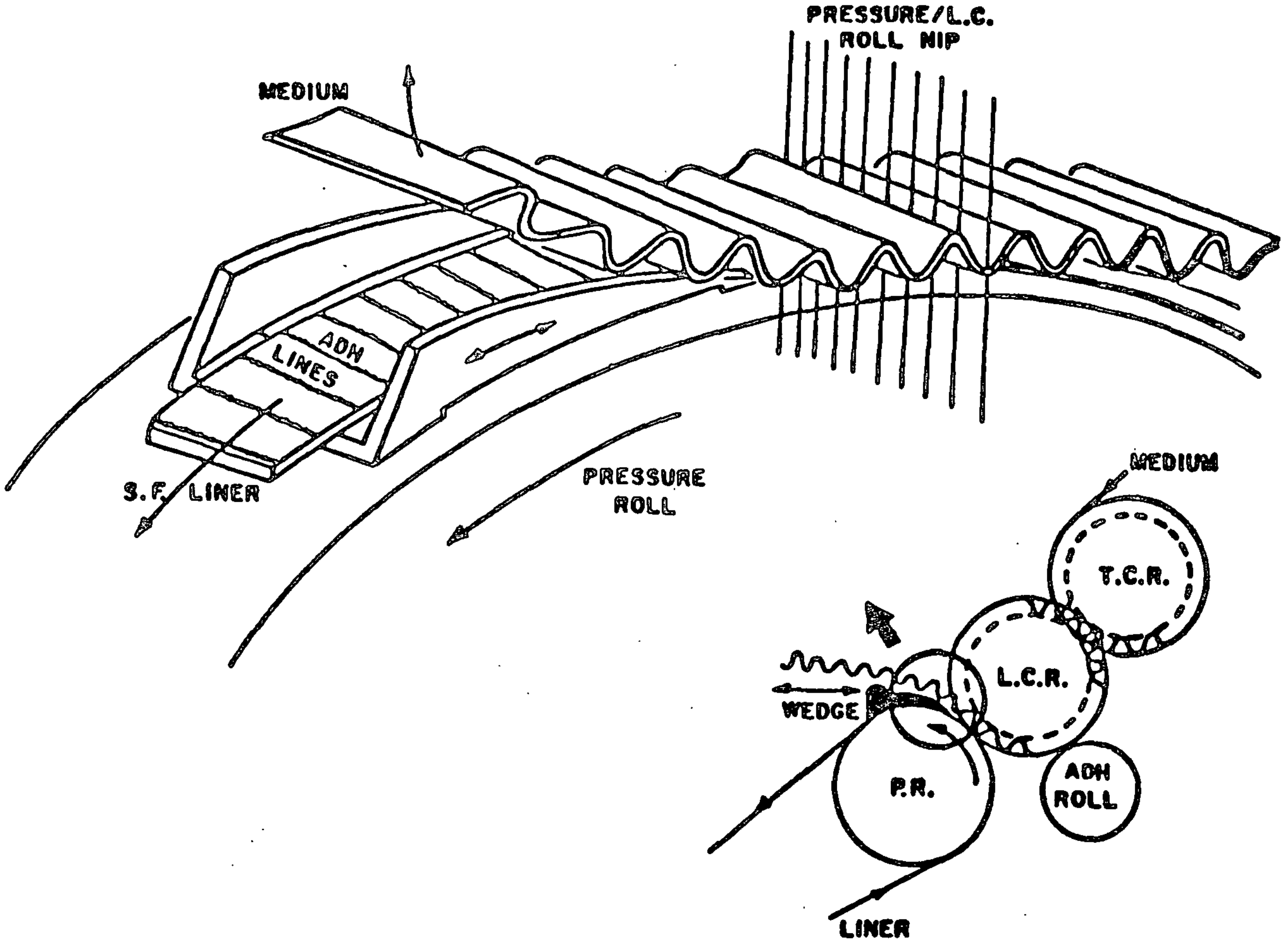
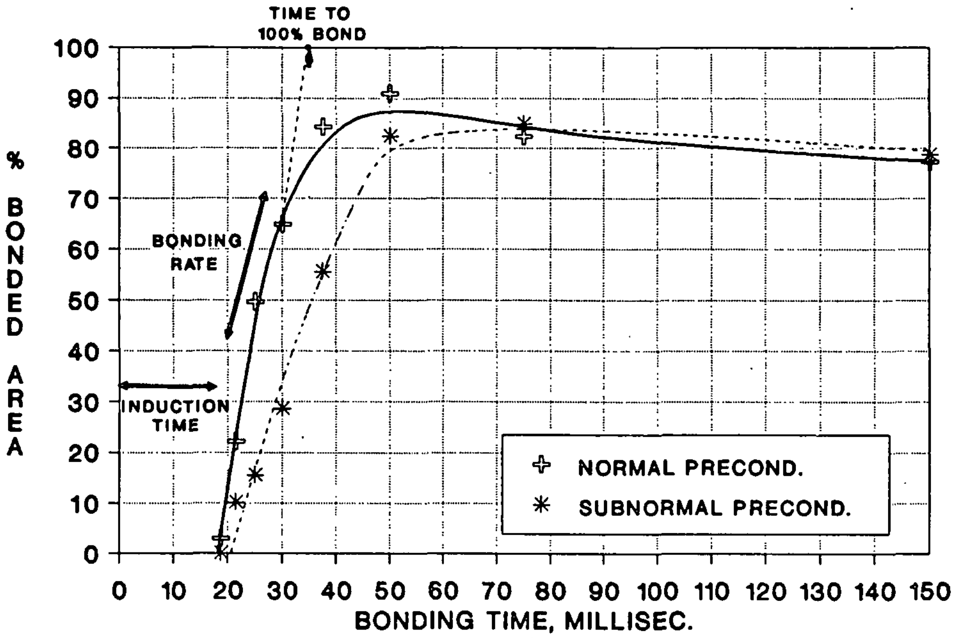
Figures and Tables

FIGURE 1
GREEN BOND STRENGTH MEASUREMENT



SINGLE-FACE GREEN BOND STRENGTH
AVERAGE OF ALL 22 COMMERCIAL
LINERBOARD SAMPLES



SINGLE-FACE GREEN BOND STRENGTH
AVERAGE OF ALL 15 COMMERCIAL
MEDIUM SAMPLES

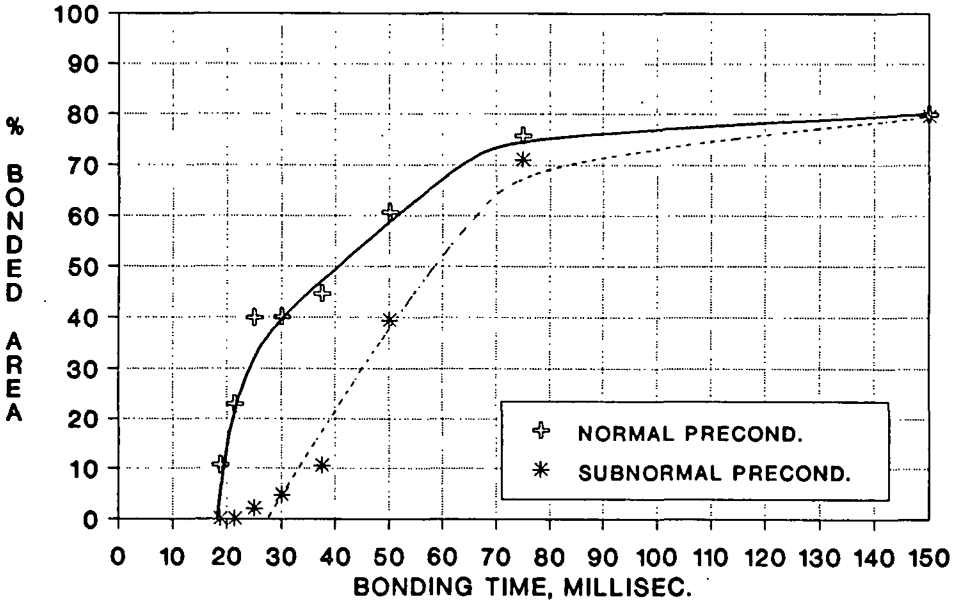


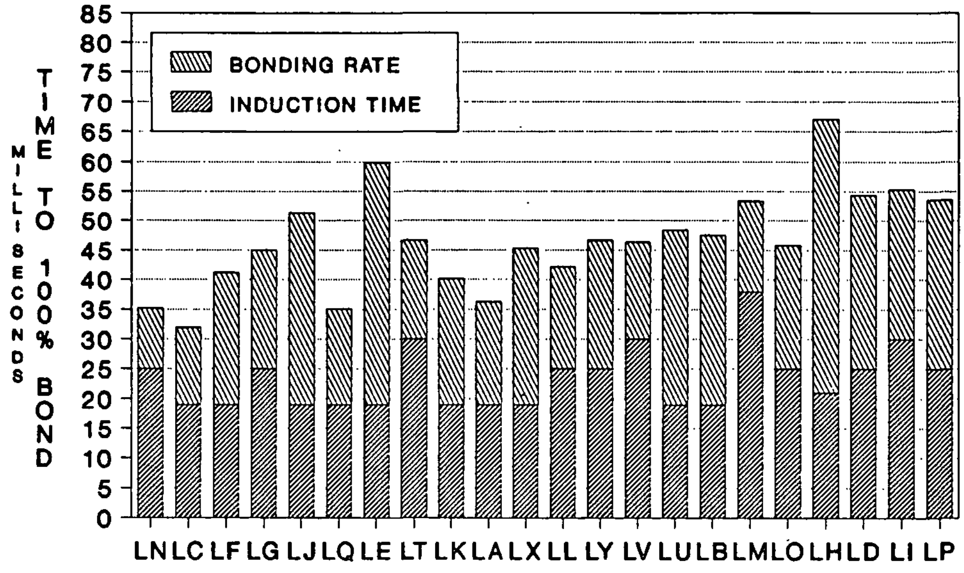
FIGURE 2

TABLE I

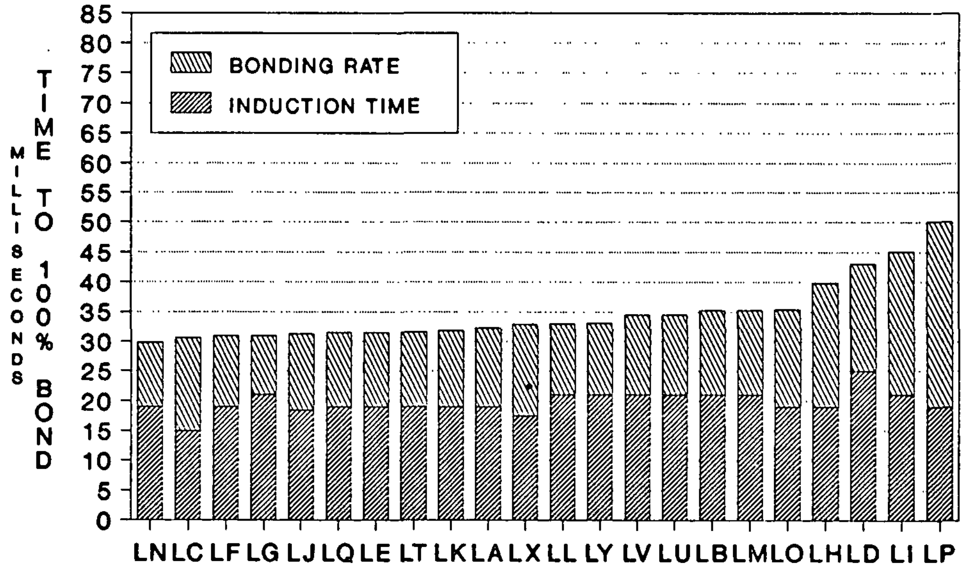
INDUCTION TIME, BONDING RATE, AND CALCULATED TIME TO 100% BOND FOR LINERBOARD AND MEDIUM SAMPLES

BONDING PARAMETER	STATISTIC VARIABLE	SUBNORMAL PRECOND.	NORMAL PRECOND.	DIFFERENCE (1)
LINERBOARD				
INDUCTION TIME (MILLISEC.)	AVERAGE	23.4	19.7	+ 15.8%
	SIGMA	5.17	1.89	+ 63.4%
	RANGE	19.0	10.0	+ 47.4%
BONDING RATE (% BOND PER MILLISEC.)	AVERAGE	4.85	7.12	+ 46.8%
	SIGMA	1.795	1.614	+ 10.1%
	RANGE	7.59	6.79	+ 10.5%
CALCULATED TIME TO 100% BOND (MILLISEC.)	AVERAGE	46.8	34.8	+ 25.6
	SIGMA	8.55	5.27	+ 38.4
	RANGE	35.2	20.4	+ 42.0
MEDIUM				
INDUCTION TIME (MILLISEC.)	AVERAGE	34.1	19.6	+ 42.5
	SIGMA	7.81	6.03	+ 22.8
	RANGE	29.0	24.0	+ 17.2
BONDING RATE (% BOND PER MILLISEC.)	AVERAGE	2.61	4.54	+ 73.9
	SIGMA	0.571	1.334	- 133.6
	RANGE	1.67	4.39	- 162.9
CALCULATED TIME TO 100% BOND (MILLISEC.)	AVERAGE	74.2	43.7	+ 41.1
	SIGMA	10.64	13.27	- 24.7
	RANGE	36.6	52.5	- 43.4

(1) DIFFERENCE IS EXPRESSED AS A % OF THE SUBNORMAL PRECONDTIONING VALUE. THE "+" SIGN INDICATES A FAVORABLE CHANGE IN BOND STRENGTH DEVELOPMENT OR VARIABILITY WITH NORMAL PREHEAT. THE "-" SIGN INDICATES AN UNFAVORABLE CHANGE.



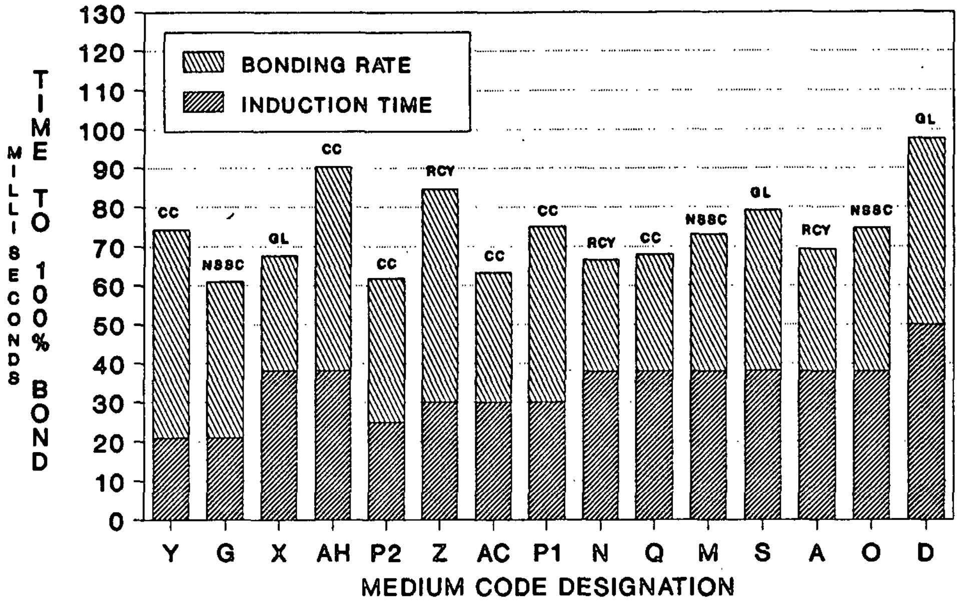
LINERBOARD SAMPLES
CALCULATED TIME TO 100% BOND
WITH SUBNORMAL PRECONDITIONING



LINERBOARD SAMPLES
CALCULATED TIME TO 100% BONDING
NORMAL PRECONDITIONING

FIGURE 3

MEDIUM SAMPLES
CALCULATED TIME TO 100% BOND
WITH REDUCED PRECONDITIONING



MEDIUM SAMPLES
CALCULATED TIME TO 100% BOND
WITH NORMAL PRECONDITIONING

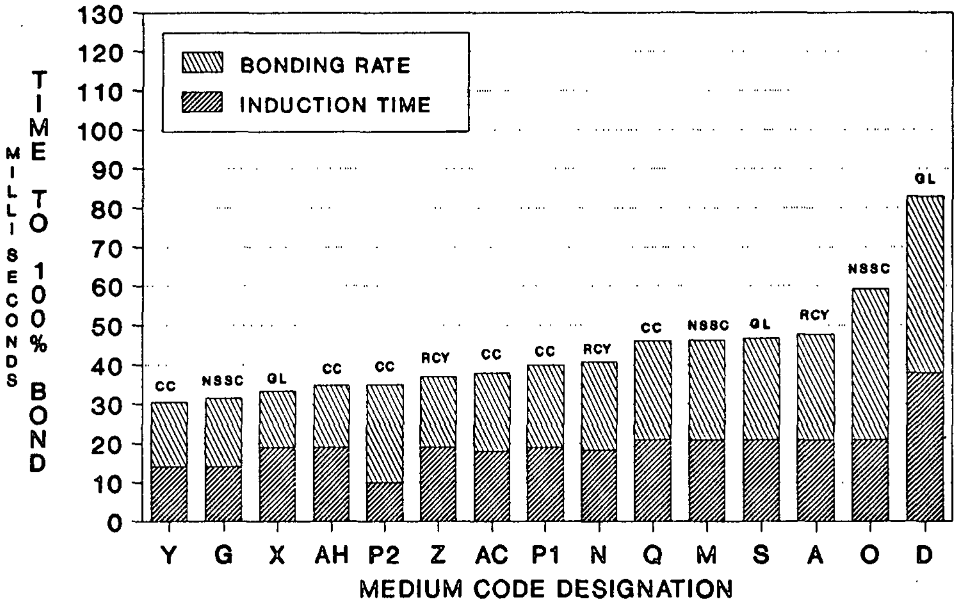
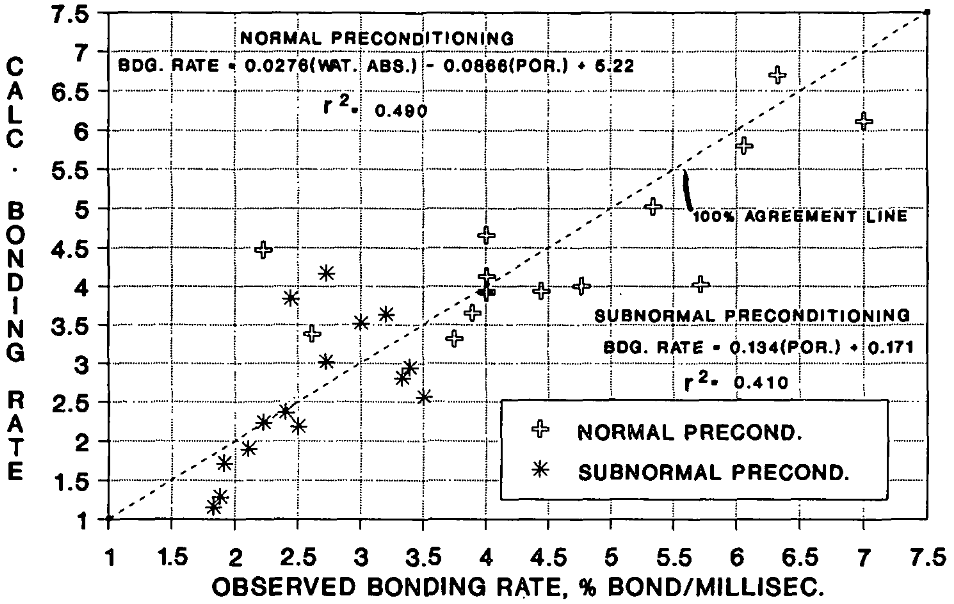


FIGURE 4

COMPARISON OF OBSERVED TO CALCULATED BONDING RATE FOR 15 COMMERCIAL MEDIUM MATERIALS



COMPARISON OF OBSERVED TO CALCULATED BONDING RATE FOR 22 COMMERCIAL LINERBOARD MATERIALS

SUBNORMAL PRECONDITIONING

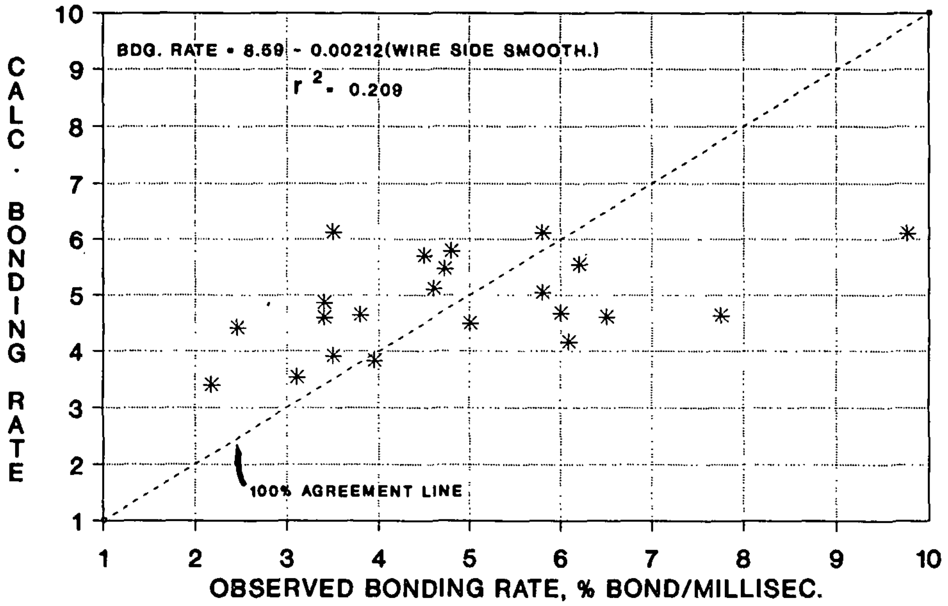


FIGURE 5

TABLE II

COMBINED BOARD PROPERTIES

PROPERTY	AVERAGE	MINIMUM	MAXIMUM	RANGE	C OF V
MEDIUM STUDY WITH NORMAL PRECONDITIONING					
FLAT CRUSH, PSI	35.9	43.3	28.8	14.5	40%
PIN ADHESION, LB	103.3	117.5	87.5	30.0	29%
EDGE CRUSH, LB/IN	42.74	46.88	40.22	6.66	16%
MEDIUM STUDY WITH SUBNORMAL PRECONDITIONING					
FLAT CRUSH, PSI	35.0	41.7	29.6	12.1	35%
PIN ADHESION, LB	100.0	118.0	76.5	41.5	42%
EDGE CRUSH, LB/IN	41.68	44.61	37.87	7.54	18%

STATISTICAL ANALYSIS OF DIFFERENCE

PROPERTY	DIFF. (N-SN)	t-VALUE	PROB. %
FLAT CRUSH	+0.89	2.393	97.5%
PIN ADHESION	+3.30	2.895	98.0%
EDGE CRUSH	+1.06	2.681	99.0%

PROPERTY	AVERAGE	MINIMUM	MAXIMUM	RANGE	C OF V
LINERBOARD STUDY WITH NORMAL PRECONDITIONING					
PIN ADHESION, LB	110.3	123.2	94.6	28.6	26%
EDGE CRUSH, LB/IN	43.82	51.15	37.97	13.18	30%
LINERBOARD STUDY WITH SUBNORMAL PRECONDITIONING					
PIN ADHESION, LB	101.6	116.9	75.9	41.0	40%
EDGE CRUSH, LB/IN	43.91	48.07	37.41	10.66	24%

STATISTICAL ANALYSIS OF DIFFERENCE

PROPERTY	DIFF. (N-SN)	t-VALUE	PROB. %
PIN ADHESION	+8.64	3.776	99.9%
EDGE CRUSH	-0.09	0.123	NOT SIG.

NOTE: MEDIUM VALUES ARE THE AVERAGE OF 37.5 & 50.0 m-s DATA.
LINERBOARD VALUES ARE THE AVERAGE OF 30 & 37.5 m-s DATA.