Development of green-bond strength in the singlefacer

Joseph J. Batelka

ABSTRACT: Development of green-bond strength on a singlefacer corrugator was measured as a function of bonding time, level of preconditioning, and physical properties of the linerboard and medium. No measurable bond strength occurs for a short period of time following application of adhesive. After this "induction time," bond strength begins to increase at a rate that is linear with time, suggesting that the green bond is formed primarily by increasing viscosity and tack as water migrates from the glue line. Green-bond strength is improved by increased preconditioning, a more porous and less wettable medium, and a smoother wire side of the linerboard.

KEYWORDS: Adhesion, bonding, bonding strength, combined boards, conditioning, corrugated boards, corrugating medium, liner boards, mechanical properties, paper properties, research, singlefaced corrugated boards, tack, time measurement, viscosity.

The quality of the bond between linerboard facings and the fluted medium is a critical factor in the performance of boxes made from corrugated board. Weak bond strength and defects such as blisters or loose edges adversely affect box performance and increase the boxplant's 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 the starch adhesive sets and forms a bond through the combined action of pressure, heat, and time.

There are two types of bonds formed on the corrugator: the singleface bond and the doubleface bond. The doubleface 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 singleface 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 singlefacer. The bond exiting this nip must be of sufficient strength to hold the web together until the bond achieves its final cure. The initial bond at the singlefacer is called the "green bond." The singleface bond cannot be reformed in subsequent stages on the corrugator if the green bond separates because of mechanical stresses. Studies have shown that formation of a singleface bond is a complex process that is affected by (a) the material properties of the paper and adhesive and (b) by the corrugator process factors of heat, moisture, pressure, and speed (*1–3*).

The corrugator bonding process has been characterized as four major steps:

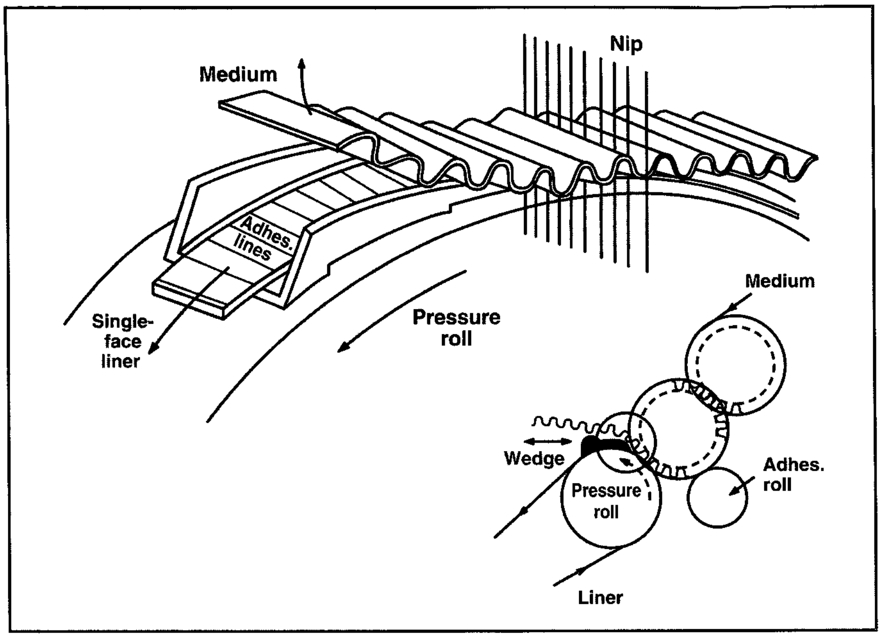
1. Application of the adhesive
2. Wetting of the substrates by the adhesive
3. Penetration of the adhesive into the substrates
4. Setting of the adhesive to form the bond.

The adhesive sets through an increase in its viscosity and tack and by the subsequent removal of water from the glue-line area (*2, 4–6*).

Microscopic examination of the singleface bond area shows that it contains four distinct areas, each with a 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*). Each of the four bond areas has distinctive characteristics. They (a) contain gelled and nongelled starch granules in differing proportions, (b) contain starch macromolecules of vary-

Batelka is a principal associate scientist at the Institute of Paper Science and Technology, 575 14th St. NW, Atlanta, GA.

1. Experimental setup. Corrugating medium is wider than linerboard and rides atop edges of the hollow wedge. The unsupported linerboard is free to separate from the fluted medium if the green bond is weak. The amount of delamination at the glue line was measured and used as a gauge of bond strength.



ing structure and location, and (c) permit starch penetration to varying degrees because of the different mechanisms governing absorption into the two substrates (*2, 5, 7–9*).

Other studies have related the cured bond strength to the paper properties, the adhesive properties, and to process conditions on the corrugator (*1–3, 10, 11*). The development of the bond strength with time also has been reported under noncorrugating conditions (*4–6*).

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

Experimental methods

All experiments were done on the Institute of Paper Science & Technology (IPST) 14-in.-wide pilot singlefacer and pilot double-backer. The paperboard used in the study consisted of 22 commercial linerboard materials (basis weight 42 lb/1000 ft^2) and 15 commercial medium materials (basis weight 26 lb/1000 ft^2) from different mills. The corrugating adhesive was the standard two-phase, 25% solids formulation used by IPST for high-speed corrugating trials.

The strength of the singleface green bond was determined using a wedge device that was located on the exit side of the nip formed by the pressure roll and the lower corrugating roll. The configuration is illustrated in **Fig. 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 as they followed the contour of the wedge edges. This upward force induced 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 glue lines. Weaker green bonds resulted in varying degrees of debonding, extending toward the center of the singlefaced web, up to the point of complete delamination of the linerboard from the medium. The amount of delamination was measured and used as a gauge of green-bond strength.

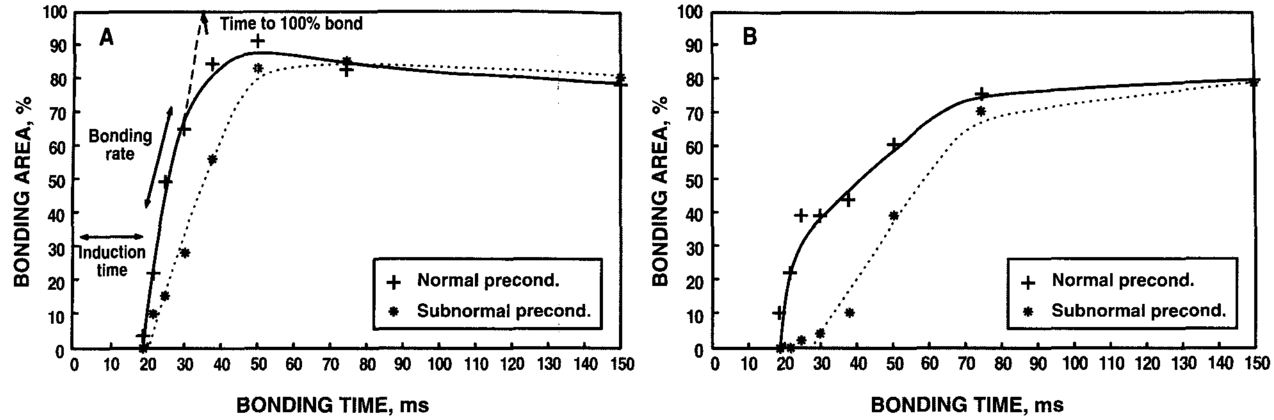
The wedge tip was located three inches from the center line of the nip between the pressure roll and the lower corrugating roll. Each of the trial materials was run at corrugator speeds ranging from 100 ft/min to 800 ft/min in 100-ft/min intervals or to the fastest speed at which 100% delamination occurred. Since the wedge position was fixed, the corrugator speed determined the amount of bonding time before application of the wedge debonding force. Bonding time varied from 150 ms at 100 ft/min to 19 ms at 800 ft/min.

Medium and linerboard were preconditioned to one of two levels. The "more preheat" condition represents the normal operating mode for the IPST pilot singlefacer. The "less preheat" condition represents a subnormal operating mode. Normal linerboard preconditioning includes a steam shower on the incoming side of the preheater. 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. Consequently, the experimental design does not allow a complete separation of the effects of bonding time and preconditioning on the bond strength development.

Green-bond strength

Percent bonded area is plotted as a function of bonding time in **Fig. 2**, which depicts average results for all linerboard samples and all medium samples at normal and subnormal preconditioning levels. The shapes of these curves are similar to those reported by Whitsitt and Lorenz for bond formation in a double-backer (*12*).

2. Development of single-facer green-bond strength at two levels of preconditioning. A: average results for 22 linerboard samples at the eight machine speeds studied. B: average results for 15 medium samples at the eight machine speeds studied.



All four curves show a finite induction time within which no bonding was observed. The induction time is followed by a linear increase in bonded area, defined here as the bonding rate. In three cases, the linear increase in bonding continued up to the maximum bond strength observed. However, the normally preconditioned medium samples (Fig. 2B) showed a different behavior, with the curve exhibiting a pronounced shoulder of reduced slope in the 30–70-ms bonding-time region. There is no explanation for this anomaly.

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-ms 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 the starch to crystallize (*2*).

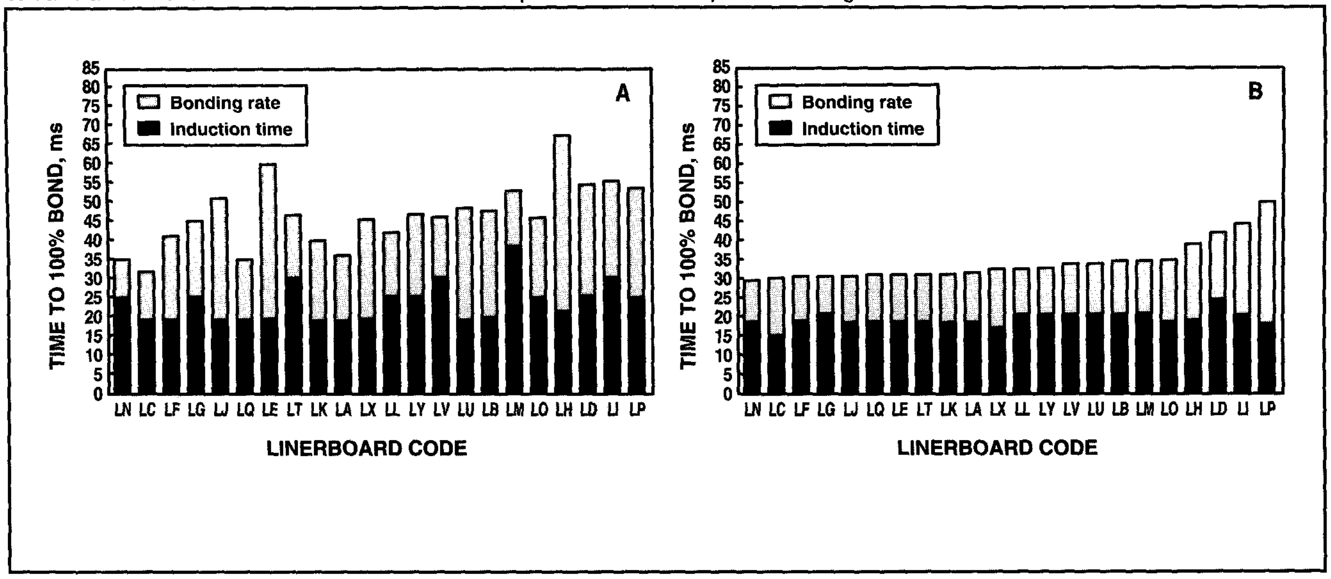
The values for induction time and bonding rate can be used to calculate a

I. Bonding parameters for samples of linerboard and medium

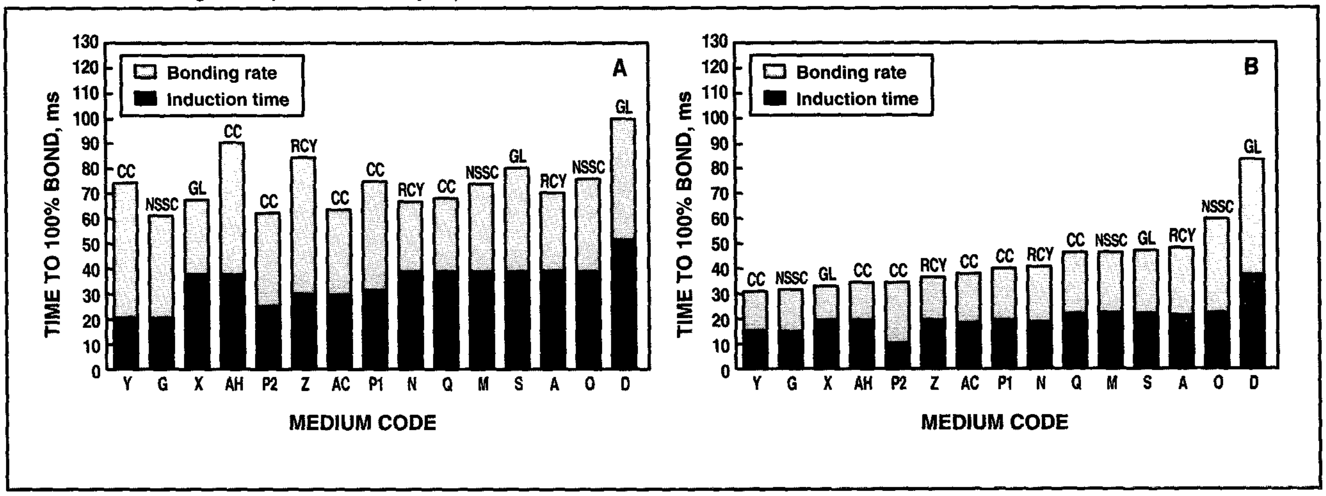
Bonding parameter	*Statistic variable*	*Preconditioning* Subnormal	Normal	*Difference,* %*
		Linerboard		
Induction time, ms	Average	23.4	19.7	+15.8
	Std. dev.	5.17	1.89	+63.4
	Range	19.0	10.0	+47.4
Bonding rate, % bond/ms	Average	4.85	7.12	+46.8
	Std. dev.	1.795	1.614	+10.1
	Range	7.59	6.79	+10.5
Calculated time to 100% bond, ms	Average	46.8	34.8	+25.6
	Std. dev.	8.55	5.27	+38.4
	Range	35.2	20.4	+42.0
		Medium		
Induction time, ms	Average	34.1	19.6	+42.5
	Std. dev.	7.81	6.03	+22.8
	Range	29.0	24.0	+17.2
Bonding rate, % bond/ms	Average	2.61	4.54	+73.9
	Std. dev.	0.571	1.334	–133.6
	Range	1.67	4.39	–162.9
Calculated time to 100% bond, ms	Average	74.2	43.7	+41.1
	Std. dev.	10.64	13.27	–24.7
	Range	36.6	52.5	–43.4

*Difference is expressed as a percentage of the subnormal preconditioning value. A plus sign indicates a favorable change in bond strength development or variability with normal preheat. A minus sign indicates an unfavorable change.

3. Calculated time to 100% bond for 22 linerboard samples at two levels of preconditioning



4. Calculated time to 100% bond for 15 medium samples at two levels of preconditioning (CC = caustic carbonate, NSSC = neutral sulfite semichemical, GL = green liquor, RCY = recycle)



time to 100% bonding, as seen in Eq. 1.

$$\text{Time to 100\% bond, ms} = \text{induction time} + (100/\text{bonding rate}) \quad (1)$$

The measured and calculated bond-development parameters for each of the four conditions are summarized in **Table I**. The results show that more preconditioning of the linerboard reduced the calculated time to 100% bond by an average of 12.0 ms, or a time reduction of 25.6%. The comparable values for the medium were 30.5 ms or 41.1%.

Data from this study indicate that added preconditioning of linerboard improves the green-bond strength predominantly by increasing the bonding rate and secondarily by reducing the induction time. For the linerboard, 69% of the improvement was due to an increased bonding rate and 31% to a reduced induction time. The improvement in green-bond strength development in medium with added preconditioning is about equally divided between the two effects. For the medium, 48% of the improvement was due to a reduced induction time and 52% to an increased bonding rate. Changes in the preconditioning of the medium have more of an effect on the green-bond strength development than do changes in the preconditioning of the linerboard, although the effect of preconditioning is important for both materials.

Figures 3 and 4 show the calculated time to 100% bond for each of the 22 linerboard materials and 15 medium materials, respectively. The results demonstrate that increased preconditioning (Figs. 3B and 4B) tends to level the influence of material properties and equalize the rate of green-bond strength development.

The data also show that no material achieved a time to 100% bond of less than 30 ms. This apparent time barrier at 30 ms is demonstrated best by the linerboard data in Fig. 3. Linerboard samples LN and LC had calculated time to 100% bond values of 30–35 ms 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 ms to 60 ms when subnormal preconditioning was used. The bonding time of these samples improved to 30 ms when normal preconditioning was used. It is hypothesized that this 30-ms 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 to bond development could be overcome and to establish which process variable has the greatest impact on bond development.

II. Average, minimum, and maximum values for variables in Eq. 2

Variable	*Average*	*Minimum*	*Maximum*
Bonding rate, % bond/ms	4.54	2.22	7.00
Water absorption (TAPPI T-819), s	32.4	3.6	97.2
Gurley porosity, s/100 mL	18.3	7.8	28.6

III. Average, minimum, and maximum values for variables in Eq. 3

Variable	*Average*	*Minimum*	*Maximum*
Bonding rate, % bond/ms	2.61	1.83	3.50
Gurley porosity, s/100 mL	18.3	7.8	28.6

IV. Average, minimum, and maximum values for variables in Eq. 4

Variable	*Average*	*Minimum*	*Maximum*
Bonding rate, % bond/ms	4.85	2.17	9.76
Bendtsen smoothness (wire side), s	1780	1158	2444

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 singlefacer (*2, 5, 7*). The adhesive 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 a fully cured bond is achieved (*5, 7*). The absorption of a starch adhesive slurry into paperboard has been shown to lack a measurable, finite wetting time, and the absorption of the starch adhesive is expected to occur simultaneously with contact (*5*). All of 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 were not the case, the bond curves shown in Fig. 2 would not have exhibited a measurable induction time. With normal preconditioning of the paperboard, a measurable green bond begins to form, on average, about 19–20 ms after exiting the pressure nip and continues to increase linearly with time. Such behavior is consistent with a bond-developing mechanism that involves an increase in adhesive viscosity and subsequent moisture migration from the glue line. The observed beneficial effect of increased preconditioning also supports this hypothesis.

Effect of material properties

Statistical regression analyses were carried out to correlate selected paper properties with induction time, bonding rate, and calculated time to 100% bond. The regressions were done separately for the linerboard and medium samples at both preconditioning levels. The tested paper properties included Gurley porosity, Bendtsen smoothness, hot friction, and various liquid absorption tests.

The only statistically significant correlations that were found (at 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 corrugating medium at normal preconditioning is shown in Eq. 2.

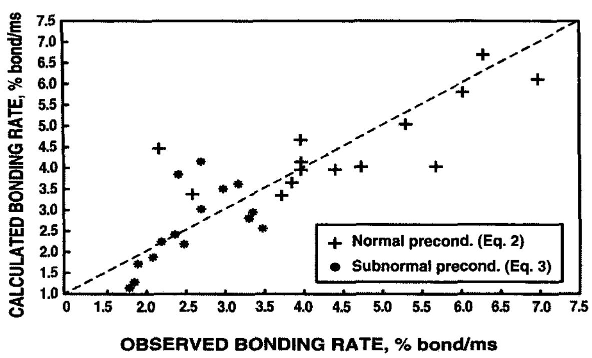
$$\text{Bonding rate} = 0.0276(\text{water absorption}) - 0.0866(\text{porosity}) + 5.22 \quad (2)$$

$$r^2 = 0.490$$

F-ratio probability = 99%

As seen in Eq. 2, the bonding rate

5. Comparison of predicted and observed bonding rates. A: results for 15 medium samples at both levels of preconditioning. B: results for 22 linerboard samples at subnormal preconditioning.



V. Combined board properties[a]

Property	*Avg.*	*Max.*	*Min.*	*Range*	*C of V,*[b] *%*	*Difference*[c]	*t-value*	*Probability, %*
				Corrugating medium				
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			
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								
Flat crush						+ 0.89	2.393	97.5
Pin adhesion						+ 3.30	2.895	98.0
Edge crush						+ 1.06	2.681	99.0
				Linerboard				
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			
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								
Pin adhesion						+ 8.64	3.776	99.9
Edge crush						- 0.09	0.123	N.S.[d]

[a]Values for corrugating medium are the average of 37.5-ms and 50.0-ms data. Linerboard values are the average of 30-ms and 37.5-ms data.
[b]Coefficient of variation
[c]Difference in values obtained for normal preconditioning and subnormal preconditioning (normal – subnormal)
[d]Not significant

increases with a more porous (lower Gurley value) and less wettable medium. Average, minimum, and maximum values for the variables in Eq. 2 are listed in **Table II**.

The strongest correlation for the corrugating medium at subnormal preconditioning is shown in Eq. 3.

$$\text{Bonding rate} = 0.134(\text{porosity}) + 0.171 \quad (3)$$

$$r^2 = 0.410$$

$$\text{F-ratio probability} = 99\%$$

As seen in Eq. 3, the bonding rate increases with a less porous medium. There is no definitive explanation for this reversal in the effect of the porosity of corrugating medium on bonding rate. However, 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 glue line. Average, minimum, and maximum values for the variables in Eq. 3 are listed in **Table III**.

The strongest correlation for the linerboard study at subnormal preconditioning is shown in Eq. 4.

$$\text{Bonding rate} = 8.59 - 0.00212 (\text{wire-side smoothness}) \quad (4)$$

$$r^2 = 0.209$$

$$\text{F-ratio probability} = 97\%$$

As seen in Eq. 4, the bonding rate increased with a smoother wire-side linerboard surface. Average, minimum, and maximum values for the variables in Eq. 4 are listed in **Table IV**. No statistically significant correlations were found between any of the bonding parameters and the properties of normally preconditioned linerboard.

These results for the singleface green bond are consistent with those reported for bond development in the double-backer. 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 bond strength development in the double-backer (*12*).

The correlations presented in Eqs. 2–4 were used to calculate bonding rates, and **Fig. 5** shows these results plotted vs. the measured results. 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.

Practical implications

The implications of the results are that the singleface 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 required green-bond strength. The various steaming and heating units on the singlefacer need to be kept in proper working condition so that they can provide the appropriate temperatures and steam quality. The containerboard 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 normal practice to reduce the preconditioning when the corrugator is slowed in order to minimize warp. The results presented here indicate that care should be taken to simultaneously increase the preconditioning when the corrugator speed is again increased. This will maintain the green-bond strength and thereby minimize the probability of generating blisters and other bonding defects.

Combined board properties

Table V summarizes the combined-board physical properties for the linerboard and medium experiments at 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, between 2.5% and 8.5%.

Conclusion

The data obtained in this study support the following conclusions and observations about the strength development of the green bond within 18–150 ms after the pressure roll nip in a singlefacer corrugator.

1. The green-bond strength development can be characterized by an induction time (during which no measurable bond strength occurs) and a bonding rate (a linear increase in bond strength over time that occurs following the induction 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 glue line. 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 by reducing the induction time and increasing the bonding rate. For medium, the effect was due equally to the two mechanisms. For linerboard, the effect was due two thirds to the increased bonding rate and one third to the reduced induction time.
4. The minimum calculated time to 100% bond was 30 ms for the process used in this experiment. Paperboard materials having a time to 100% bond of 30 ms with reduced preconditioning did not exhibit an improvement when more preconditioning was used.
5. Specific paper properties were correlated to the bonding rate. With normal preconditioning, bonding was enhanced by mediums that were

more porous and less wettable. With subnormal preconditioning, bonding was enhanced by mediums that were less porous and by linerboard with a smoother wire-side surface.

6. Increased preconditioning improved the pin adhesion, flat crush, and edge crush test of the cured combined board.
7. The results suggest that the level of preconditioning should be increased when corrugator speed is increased. Doing so will minimize the probability of weak bonds or bonding defects.

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