Development of green-bond strength in the singlefacer: Part 2

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ABSTRACT: Development of green-bond strength on a singlefacer corrugator was measured as a function of five variables: moisture content and temperature of the corrugating medium and the linerboard, and the bonding time. Increasing any of these variables (within the ranges investigated) improved development of green-bond strength. Moisture content of the medium had the greatest effect, followed by the linerboard moisture content. Bonding time and web temperature had lesser effects that were approximately equal in magnitude. The 19-ms induction-time barrier reported in Part 1 of this study appears to have been an artifact of the experimental procedure, where corrugator speed was adjusted to vary the bonding times. The results in Part 2 indicate that the green bond exiting the pressure-roll nip is weak but measurable when the moisture contents and temperatures of the webs are at appropriate levels. Higher average rollstock moisture contents at the mill should improve development of green-bond strength.

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

The structural strength of corrugated board depends on (a) the strength of the containerboard materials, (b) the integrity of the shape of the fluted corrugating medium, and (c) the strength of the bond between the medium and the linerboard facings. The bond is formed by applying a starch adhesive to the tips of the fluted medium and bringing these tips into contact with the linerboard facings. A combination of heat, pressure, and time is used to set the adhesive and to form the final cured bond.

Formation of both the single-face and double-face bonds is affected by the preheating and preconditioning of the respective webs that occurs before the adhesive-covered flute tip is brought into contact with the linerboard. The double-face bond continues to be exposed to both heat and pressure in the double-backer as the bond forms. The single-face bond, on the other hand, is under pressure and heat only in the nip between the lower corrugating roll and the pressure roll in the singlefacer. The single-faced board exiting this nip must remain intact, without the aid of additional heat or pressure, until the final bond is formed. The uncured bond is known as the "green bond," and it is extremely weak upon exiting the singlefacer nip. Any separation of this green bond is permanent, since the bond cannot be re-formed during the remainder of the corrugating process. Such separations produce corrugated board defects commonly known as "blisters," "fluff-out," "loose bond," and "loose edges."

Studies on the nature of this green-bond development have been reported in the literature. Most of these studies have involved (a) inferences based on examination of the fully cured bond or (b) direct exami-

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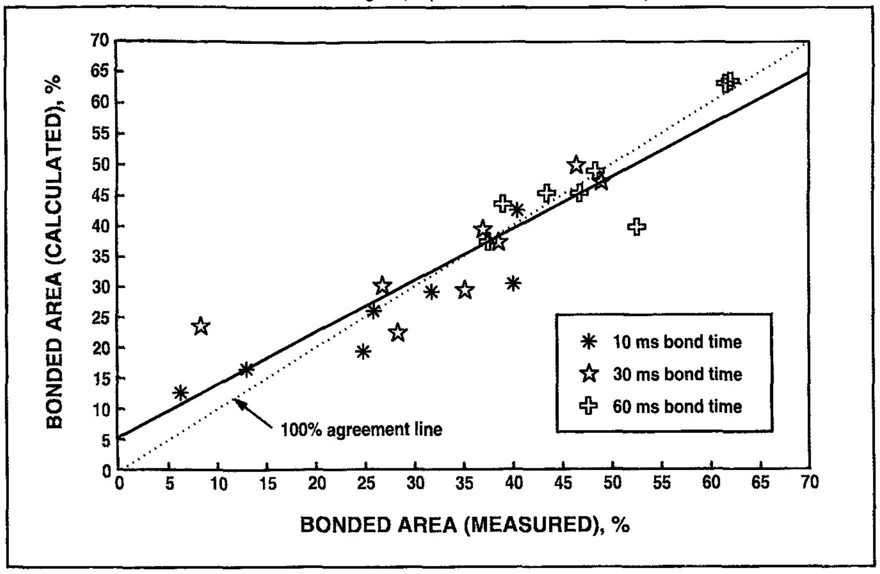
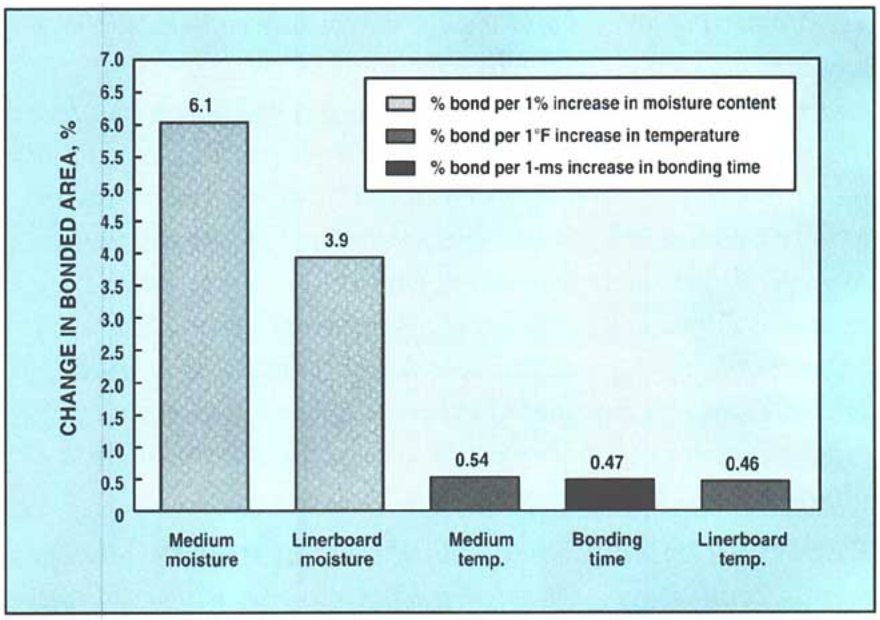
nation of the green bond under noncorrugating conditions *(1–8)*. A recent publication by the author *(9)* evaluated the strength of the green bond under actual corrugating conditions over the bonding time range of 19 ms to 150 ms. In that study, the bonding time was changed by adjusting the corrugator speed. The change in corrugator speed also affected the preconditioning levels of the linerboard and medium. Moisture and temperature measurements of the linerboard and medium were not available. Therefore, that study did not allow the complete separation of the moisture, temperature, and time effects on the strength development of the green bond.

The objective of the present study was to characterize the green-bond strength development under actual corrugating conditions over a bonding time range of 10–60 ms, and to determine the independent effects of the five process variables of medium moisture, linerboard moisture, medium temperature, linerboard temperature, and bonding time.

1. Observed vs. calculated bond strength (Eq. 1, $r^2 = 0.806$, $n = 23$)



2. Change in bonded area per unit change in the five experimental variables



Experimental techniques

All of the experiments were done on the 14-in.-wide pilot-scale singlefacer at the Institute of Paper Science & Technology (IPST). The containerboard used consisted of a 42-lb/1000 ft^2 commercial linerboard and a 26-lb/1000 ft^2 commercial medium. The corrugating was done using C-flute rolls and the standard two-phase, 25% solids starch adhesive used at IPST for corrugating trials.

The level of preconditioning was adjusted to vary the temperatures and moisture contents of the webs (linerboard and medium) entering the singlefacer. The temperature and moisture contents of both webs were measured continuously by gauges located after all of the preconditioning units and as close as physically possible to the point of entry of the webs into the singlefacer.

The green-bond strength was measured by the use of a debonding wedge device located at the exit side of the pressure-roll nip. The degree of debonding was used as a gauge of the green-bond strength *(9)*. The debonding wedge was supported by a holder that allowed the wedge to be positioned at distances ranging from 1 in. to 6 in. from the nip. The holder was designed to maintain a constant web contact angle, and therefore a constant debonding force, at all wedge positions. The corrugator was run at a constant speed of 500 ft/min for all of the experiments. Bonding time was controlled solely by changing the position of the wedge.

Experimental results

The experiment consisted of a total of 23 combinations of different variable levels. The ranges for moisture content were 5.66–9.68% for the medium and 6.41–10.58% for the linerboard. The ranges for temperature were 171–196°F for the medium and 176–232°F for the linerboard. The range for bonding time was 10–60 ms.

Multiple linear regression analysis showed that all five variables had statistically significant effects on the green-bond strength development. The regression equation (r^2 = 0.806, n = 23) is

$$B = 6.059M_M + 3.939M_L + 0.544T_M + 0.461T_L + 0.474t_B - 257.7 \quad (1)$$

where

B = percent bonded area

M_M = moisture content of medium, %

M_L = moisture content of linerboard,%

T_M = temperature of medium, °F

T_L = temperature of linerboard, °F

t_B = time of bonding before wedge, ms.

Figure 1 is a plot of the calculated bonded area vs. the observed bonded area. The r^2 value of 0.808 indicates a reasonably good accuracy and precision for the regression equation.

The regression model shows that the green-bond strength development is improved by higher moisture contents and temperatures of both the linerboard and medium and by longer bonding times. The constants shown in Eq. 1 represent the change in percent bond per unit change in the variable. The relative effects of each of the five variables is shown in **Fig. 2**. The moisture content of the medium had the greatest effect, with a 6.1-percentage-point change in bond strength per 1% change in moisture content. The second greatest effect was the linerboard moisture content, with a 3.9-percentage-point change in bond strength per 1% change in moisture content. The effects of the medium temperature, the linerboard temperature, and the bonding time were approximately equal, being 0.54, 0.46, and 0.47, respectively.

The results indicate that higher average rollstock moisture levels from the mill should improve green-bond development on the singlefacer corrugator, provided that the higher averages are consistent with moisture uniformity. However, care should be exercised in extrapolating the regression equation variables shown in Eq. 1 greatly beyond the ranges of the variables achieved in this study. For example, it has been shown that overheating the webs can reduce green-bond strength by crystallizing the adhesive *(2, 9)*. Practical experience has also shown that excessively high moisture content of the webs can reduce green-bond strength.

The prior work reported in this experimental series indicated an induction-time barrier of 19 ms before any measurable green-bond strength was achieved *(9)*. Based on the results of this study, it appears that this induction-time barrier was an artifact created by the experimental technique of adjusting the corrugator speed to vary the bonding time. The regression model shown in Eq. 1 predicts a weak green-bond strength at zero time. For example, the regression equation predicts a bonded area of 16% at zero bonding time, i.e., exiting the pressure-roll nip, for the average linerboard and medium temperatures (204°F and 184°F, respectively) and the average linerboard and medium moisture content levels (8.50% and 7.67%, respectively) measured in this study.

Conclusions

The data from this study support the following conclusions:

1. Higher moisture content and higher temperature of the corrugating medium and linerboard at the point of entering the singlefacer roll stack improve the development of green-bond strength.
2. The green-bond strength increases linearly with bonding time once the bond starts to form.
3. On a per-unit-change basis, the moisture content of the medium has the greatest effect on green-bond strength development, followed by the linerboard moisture content. The effects of medium and linerboard temperature and the bonding time are smaller and about equal in magnitude.
4. Extrapolation of the regression equation indicates that a weak but measurable green-bond strength exists at zero time, i.e., exiting the pressure-roll nip, provided that the medium and linerboard webs are sufficiently high in moisture content and temperature.
5. Higher average rollstock moisture contents at the mill should improve development of green-bond strength at the corrugator singlefacer, provided that the higher average moisture content is consistent with uniform moisture profiles.

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