The effect of boxplant operations on corrugated board edge crush test

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ABSTRACT: The quantitative effect of five boxplant process variables on both the average edge crush test (ECT) and the ECT variability of corrugated board, and its impact on the ability to achieve Alternate Item 222/Rule 41 ECT compliance, was studied. The process variables were crushing, single-facer cured bond strength, leaning flutes, high/low flutes, and pressure roll cutting. The experimental results show that a lower single-face pin adhesion bond strength, a greater angle of leaning flutes, a greater percentage of high/low flutes, and crushing of the combined board all adversely affect the average ECT. Moderate increases in the pressure roll cutting of the linerboard improved the average ECT. No variable interaction effects were found.

KEYWORDS: Bonding strength, corrugated boards, crushing, cutting, edge crush tests, flutes, freight classification, hi lo flutes, process variables, standards.

The recent adoption of Alternate Item 222 and Rule 41 has accelerated the marketplace's interest in compressive strength performance packaging. The edge crush test (ECT) of the corrugated board has been shown to be the most important combined board property controlling box compressive strength *(1)*. The ECT has been shown to be related primarily to the cross-direction edge crush strength of the linerboard and the medium *(2, 3)* and to the quality of the boxplant converting operations *(4–7)*. These referenced studies have evaluated the effect of single variables, not the combined effect of several variables.

Our project studied the quantitative effect of five selected boxplant process variables on both the average ECT and the ECT variability of corrugated board, and its impact on the ability to achieve Alternate Item 222/Rule 41 ECT compliance The process variables studied were crushing, single-facer cured bond strength, leaning flutes, high/low flutes, and pressure roll cutting.

Experimental methods

The experimental corrugated board used in this study was produced on the Institute of Paper Science and Technology (IPST) 14-in.-wide pilot corrugator at commercial speeds. All of the board was fabricated from a single roll of commercial 26-lb/1000 ft^2 corrugating medium and a single roll of commercial 42-lb/1000 ft^2 linerboard. A standard two-phase, 25% solids adhesive was used.

The techniques used to change the levels of the process variables studied were the same conditions that would exist in a commercial boxplant. The single-face bond strength was changed by varying the adhesive application rate. The magnitude of the high/low flutes was changed by adjusting the medium web tension and the upper corrugating roll pressure. The degree of leaning flutes was changed by passing the single-faced web through a roll nip with the flute axis parallel to the roll axis. Pressure roll cutting of the linerboard was changed by changing the gap between the lower corrugating roll and the pressure roll. Crushing was varied by passing the single-wall board through a hard rubber-covered roll nip of known gap, with the flute axis perpendicular to the roll axis.

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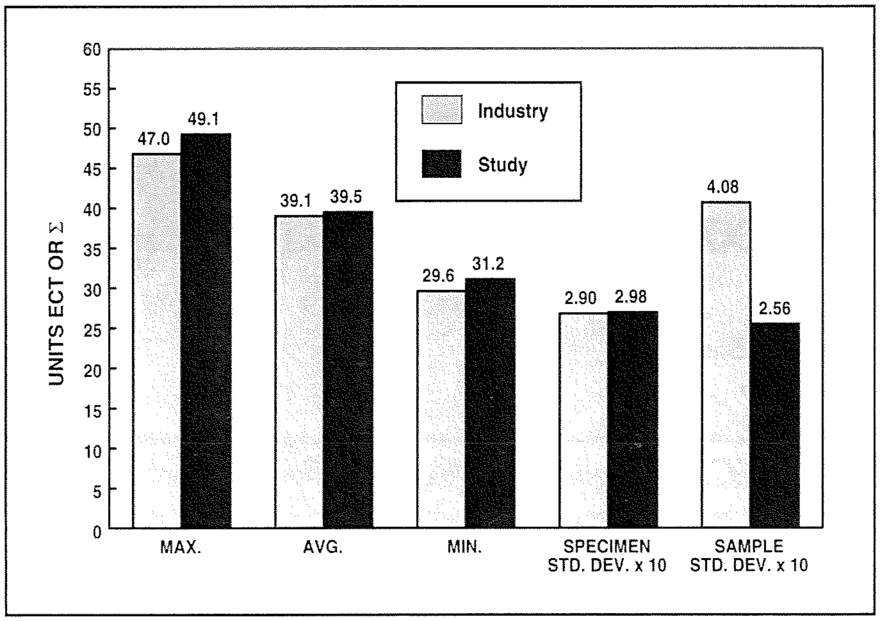
TAPPI test methods were followed for all of the combined board physical tests. The steel platen method was used for the caliper measurements. The high/low flutes were measured using the IPST laser flute height tester. The degree of pressure roll cutting was quantified by the mullen test values of the single-wall board. The average ECT value for each experimental variable combination is based on 10 replicate measurements. All of the samples were preconditioned and conditioned according to TAPPI methods prior to testing.

Analysis of results

The experimental design included three levels of single-face bond strength, three levels of high/low flutes, two levels of leaning flute, two levels of pressure roll cutting, and six levels of crushing. A full-factorial experimental design was used, resulting in a total of 216 variable combinations. The complete compilation of the ECT values for each of the 216 conditions requires 12 pages of tables, and is, therefore, too extensive to be included in this publication. For this reason, only the average measured value for each process condition and the corresponding average measured ECT are shown in **Table I**. The full-factorial data set is presented in the appendix of the final report prepared for the sponsors of this research. The sponsor may be contacted concerning obtaining the full set of factorial data *(8)*.

The variable levels achieved represent a range consistent with poor to excellent commercial quality. Materials so poor in quality as to be noncommercial in nature were not included. The experimental ECT levels obtained in this study are compared to industry ECT data in **Fig. 1** *(2, 9)*. The experimental ECT average, minimum, maximum, and specimen standard deviation values match those of the commercial product, indicating that the experimental objective was met.

1. Comparison of experimental material to industry material

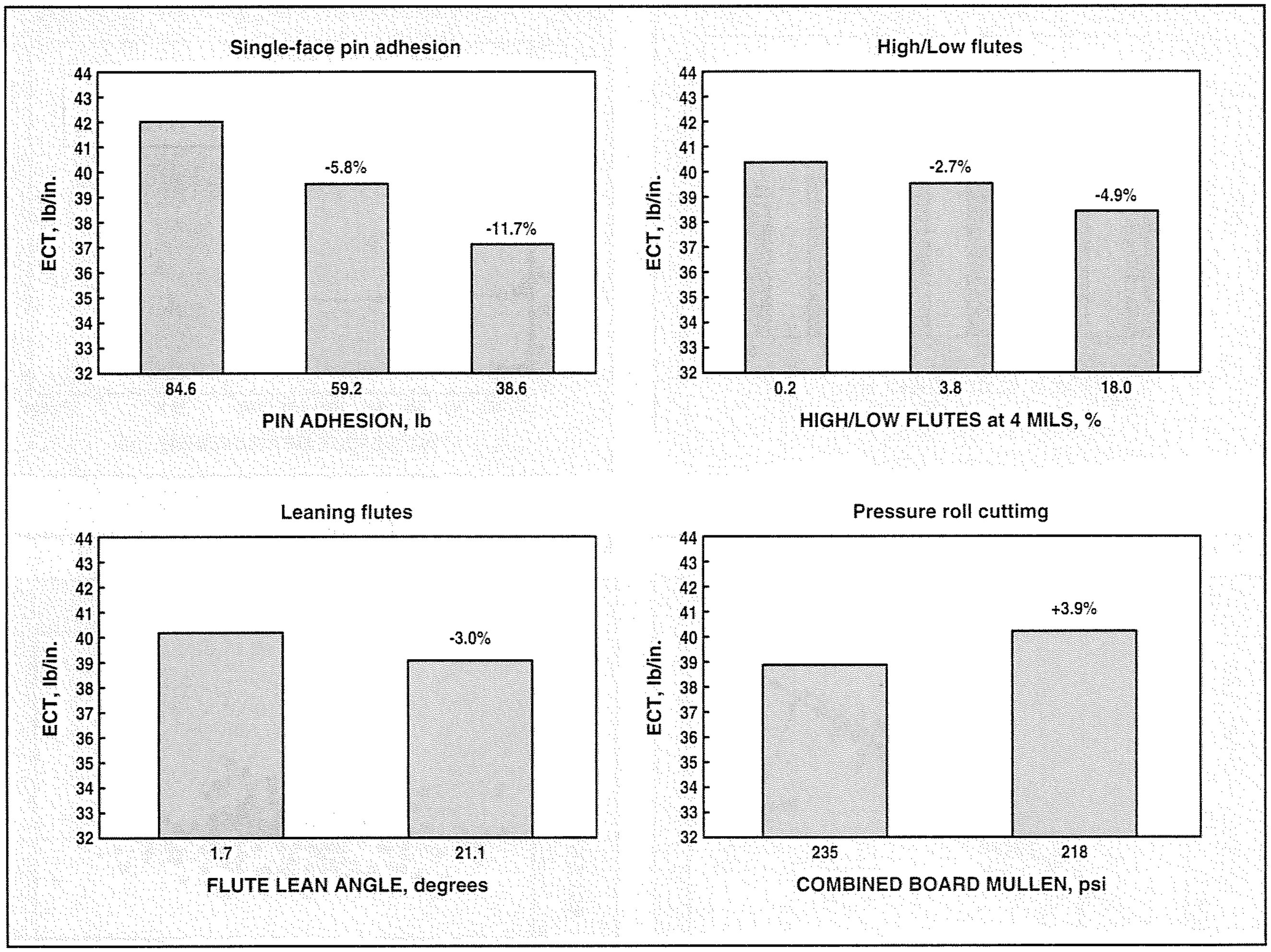


I. Experimental design—full factorial

Single-face pin adhesion, lb		
84.6	=	42.0 lb/in. average ECT
59.2	=	39.5 lb/in. average ECT
38.6	=	38.6 lb/in. average ECT
High/low flutes, % at or above 4 mils		
0.2	=	40.4 lb/in. average ECT
3.8	=	39.6 lb/in. average ECT
18.0	=	38.5 lb/in. average ECT
Leaning flute, angle from vertical		
1.7	=	40.2 lb/in. average ECT
21.1	=	39.0 lb/in. average ECT
Pressure roll cutting, psi mullen		
235	=	38.8 lb/in. average ECT
281	=	40.3 lb/in. average ECT
Actual crushing, mils		
0	=	42.8 lb/in. average ECT
8	=	40.5 lb/in. average ECT
15	=	39.9 lb/in. average ECT
25	=	38.3 lb/in. average ECT
35	=	38.4 lb/in. average ECT
50	=	37.2 lb/in. average ECT

The sample average ECT standard deviation for the commercial product was significantly greater than that for the experimental material. A comparison of these standard deviation values to the respective range values indicates that the experimental data have a reasonable normal distribution shape, while the commercial data are skewed. This skewed distribution for the commercial product explains the higher ap-

2. Average effects of process variables on ECT



parent sample average ECT standard deviation.

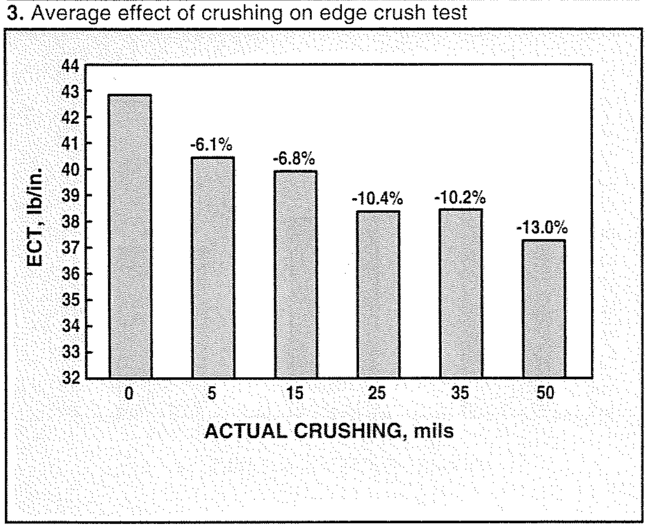
The average effects of the process variables of single-face pin adhesion, high/low flutes, leaning flutes, and pressure roll cutting of the linerboard are shown in **Fig. 2**. Over the ranges of the variables shown in Table I, a lower single-face pin adhesion reduced the average ECT by 11.7%, an increased percentage of high/low flutes at 4 mils or greater reduced the average ECT by 4.9%, increased leaning flutes decreased the average ECT by 3.0%, and increased pressure roll cutting, as indicated by reduced mullen strength, increased the average ECT by 3.9%. Our hypothesis is that the improved ECT observed with the pressure roll cutting may be attributed to a decoupling of the stress/strain imbalance between the linerboard and the medium *(10)*.

The double-back pin-adhesion bond strength was not included as a separate variable in this study. However, there is no reason to believe that its effect would be different than that observed for the single-face pin adhesion bond strength. A bond effect is a bond effect. Therefore, we suggest that the effect of the double-back bond strength would be equal to that observed for the single-face bond and that it can be quantitatively treated as such for boxplant ECT quality control strategies. The adverse effect of a lower bond strength on the ECT is in agreement with prior published studies *(4, 5)*.

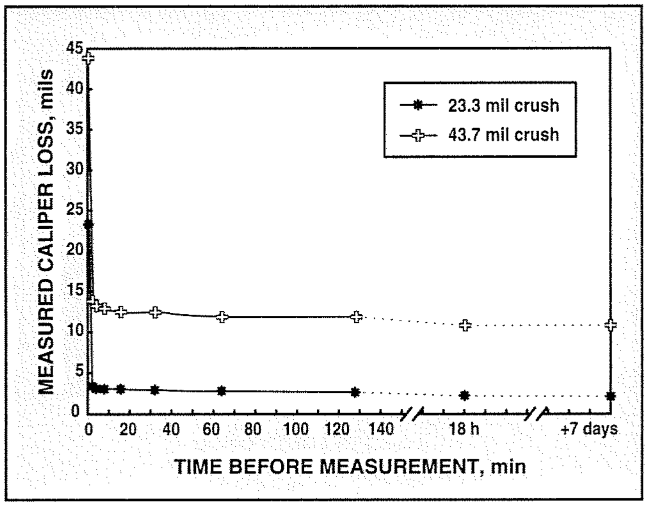
The effect of combined board crushing on the average ECT is shown in **Fig. 3**. An actual 50-mil crushing produced an average ECT reduction of 13.0%. These results are not consistent with a prior published study that reported an increase in average ECT with crushing *(7)*, but are consistent in trend with other published studies *(5, 6)*.

Combined board caliper measurements are frequently used in boxplants as a method for controlling actual crush occurring in the process. **Figure** 4 shows that the measured crush is significantly less than the actual crush due to the ability of the fluted medium to recover in caliper. An actual crush of 23 mils resulted in a measured crush of only 3 mils. An actual crush of 44 mils resulted in a measured crush of only 7 mils. These results are consistent with the observations of prior published studies *(5, 11)*. What is even

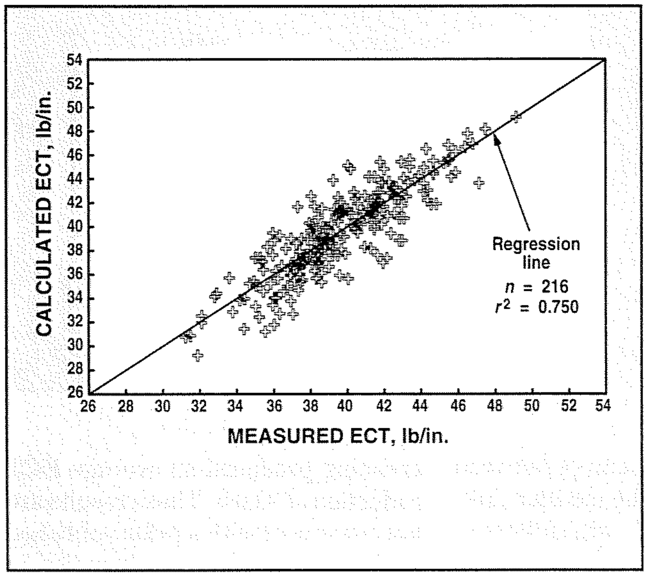
3. Average effect of crushing on edge crush test



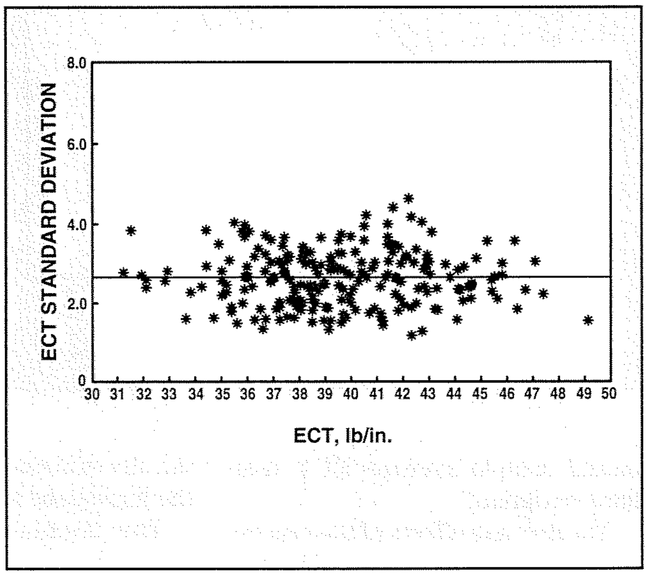
4. Effect of recovery time on measured caliper after crushing



5. Comparison of calculated ECT to observed ECT



6. Relationship of average ECT to ECT standard deviation



more significant is that almost all of the caliper recovery occurred within one minute of the actual crushing. This recovery speed is too fast to make boxplant caliper measurements a sensitive tool for judging actual crushing.

The leaning flute defect also resulted in an average combined board caliper loss of 21 mils. Statistical analysis showed that there was no ECT interaction effect between caliper loss due to leaning flute and caliper loss due to crushing. The two effects are additive. These results demonstrate a second weakness of boxplant combined board caliper measurements as a quality control tool. Caliper measurements alone do not differentiate between crushing and leaning flute defects. Statistical analysis also showed no significant ECT interaction relationships between any of the other variables.

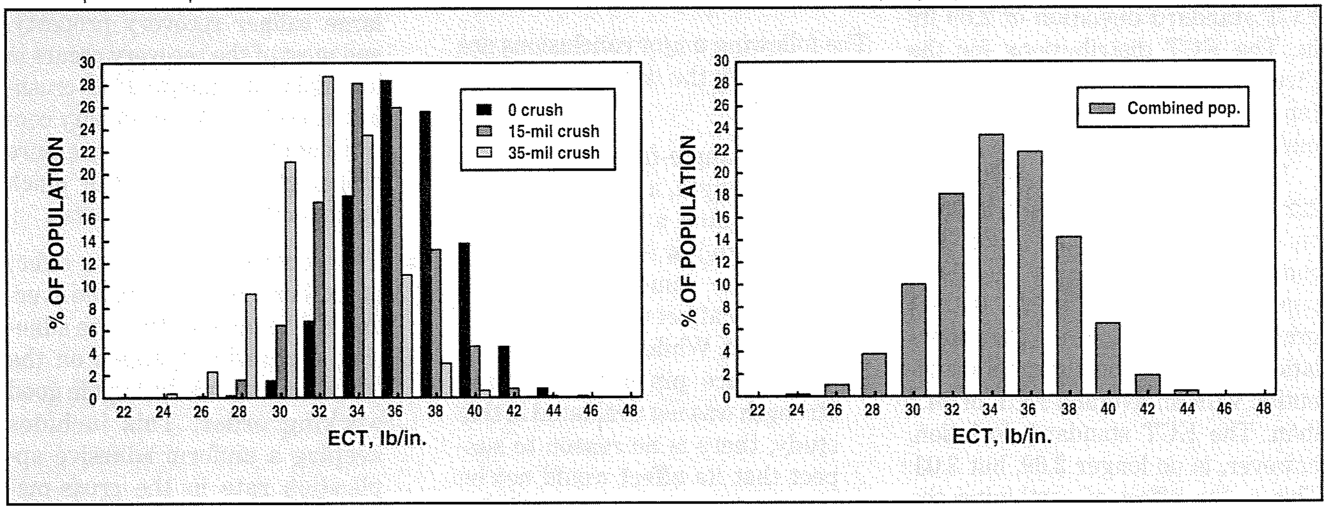
Multiple linear regression analysis was performed on the 216 total variable combinations. The regression equation is shown below, and a plot of the calculated ECT, using the regression equation versus the measured ECT, is shown in **Fig. 5**.

$$ECT = 33.71 - 0.0397\,(LF) + 0.150\,(SFPA) - 0.0534\,(H/L) - 0.134\,(act.\ crush) - 0.130\,(\%\ mullen\ loss)$$

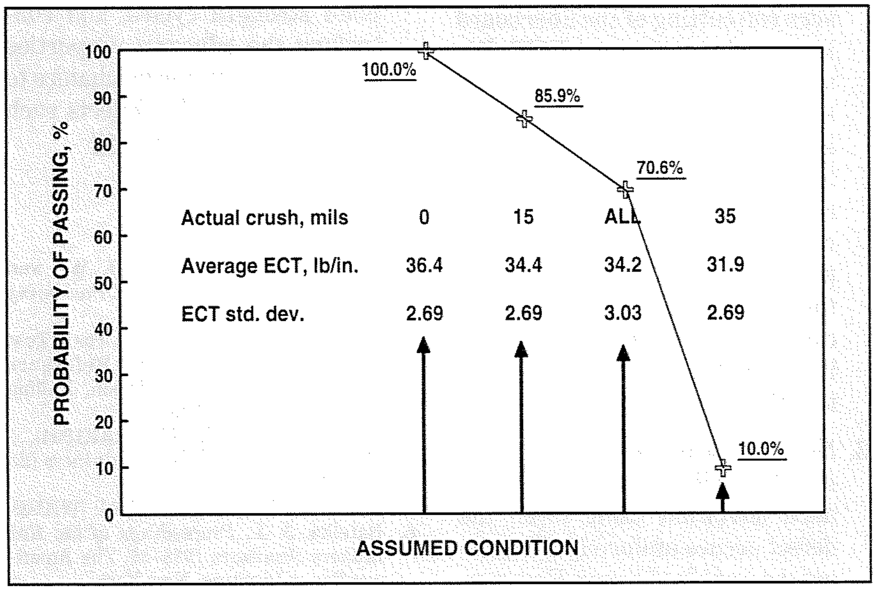
where

n	= 216
LF	= leaning flute angle, degrees
SFPA	= single-face pin adhesion, lb
H/L	= high/low flutes at 4 mil or more, %
act. crush	= actual crush occurring, mils
% mullen loss	= [(actual – highest)/highest]100.

7. Example of multiple defect situation on ECT distribution for three different crush levels equally represented



8. Theoretical example of effect of combined defects on Item 222/Rule 41 ECT compliance



The r^2 correlation coefficient was 0.750, and the average, absolute error of the estimated ECT values was 1.52 lb/in. The average 95% confidence limit of the measured ECT values was 1.85 lb/in. This indicates that the regression equation results are as good as can be statistically expected based on the experimental uncertainty of the measured average ECT.

The compliance probability for Item 222/Rule 41 certification involves both the average ECT and the ECT standard deviation *(12)*. The ECT standard deviation is plotted against the average ECT in **Fig. 6**. The regression line is statistically flat, indicating no correlation between the two parameters. This indicates that the reduction in average ECT due to the process variables studied does not change the observed standard deviation, provided the defect is evenly and uniformly present throughout the entire sample being tested. Standard deviation is constant over the range of ECT values from 31 lb/in. to 49 lb/in. The observed standard deviation would increase if the defect was not constant over the entire sample. This is due to the fact that the sample would consist of two or more populations with different average ECT values.

The following is an example of the effect of combined populations on Item 222/Rule 41 ECT certification compliance probability. The example is based on the crushing variable. Assume that a 30,000 run box, 32 lb/1000 ft^2 ECT grade, C-flute construction order is being run on a corrugator following a B-flute order. The first 10,000 sheets are crushed an assumed 35 mils before the dry end crew measures a 4.4-mil lower than expected caliper for the grade. The wet-end machine tender remembers that he forgot to adjust the rider roll and makes an adjustment. The next 10,000 sheets are run, and the crew sees that the caliper is still running 1.6 mils lower than standard. These sheets were, then, actually crushed 15 mils. The rider roll is again adjusted, and the final 10,000 sheets are run to the standard caliper and without excessive crushing.

Since actual crushing reduces the average ECT, the three actual crushing levels of 35, 15, and 0 mils (measured crush of 4.4, 1.7, and 0 mils) result in populations with three different ECT averages. In the assumed example, the 35-mil crushed board averages 31.9 lb/in. ECT, the 15-mil crushed board averages 34.4 lb/in. ECT, and the zero crushed board averages 36.4 lb/in. ECT. Since the crushing does not affect the ECT standard deviation, each of the three populations has the same ECT standard deviation of 2.69 lb/in. The ECT distributions for the three populations are shown in the top graph of **Fig. 7** and are all normal in shape.

However, the compliance with Item 222/Rule 41 ECT certification is based on all 30,000 bases in the order. The combined distribution of the three populations is shown in the bottom graph of Fig. 7. To the eye, the population appears to be a normal distribution with an average ECT of 34.2 lb/in. The ECT standard deviation, however, is no longer 2.69, but 3.03. This is the effect of combining the three populations.

The average ECT and the ECT standard deviation values can be used to statistically predict the expected Item 222/Rule 41 compliance probability *(6)*. The compliance probability calculations are based on an assumed unbiased sampling from the entire population and are shown in **Fig.** 8. The zero crushed boxes would achieve a 100% probability of compliance. The 15-mil crushed boxes would have an 86% probability of compliance, and the 35-mil crushed boxes would have a 10% probability of compliance. The compliance probability for the entire population would be 71%, even though the average ECT is equal to that of the 15-mil crushed boxes. The reduction in the compliance probability from 86% to 71% is due to the higher ECT standard deviation, 3.03 versus 2.69.

The same principles described above also will hold for other examples of combined populations. Some other examples that might be expected in a boxplant would be localized crushing, high/low flutes occurring in a machine-direction cycle on the corrugator due to a loping roll of medium or to vibration in the single-facer roll stack, or variation in the bond strength due to such factors as nonuniform cross-direction adhesive application rates, an out-of-round adhesive doctor roll, or mottled or ringed adhesive patterns on the glue applicator roll.

Conclusions

The following major conclusions are supported by the data presented in this report:

1. A lower single-face pin adhesion bond strength, a greater angle of leaning flutes, a greater percentage of high/low flutes, and crushing of the combined board all adversely affect the average edge crush test. While the effect of the double-face pin adhesion bond strength was not evaluated in this study, there is no reason to suspect that its effect would not be identical to that observed for single-face bond strength.

2. Moderate increases in the pressure roll cutting of the linerboard improved the average ECT. We think this effect can be explained by the decoupling of the stress/strain differences between the linerboard and medium under compression loading. We do not recommend that a boxplant use pressure roll cutting to improve the average ECT. Such an action could be detrimental to the ability of the box to contain and protect the packaged product.

3. None of the process variables affect the within-sample ECT standard deviation value when the defect occurs uniformly throughout the combined board. However, localized defects such as nonuniform crushing or variable bond strength will produce a higher effective ECT standard deviation due to the combination of different average ECT populations, and, therefore, adversely affect the Item 222/Rule 41 ECT probability of compliance.

4. No variable interaction effects were found. The effect of the variables is additive and can be modeled by a multiple linear regression equation.

5. The degree of crushing determined by caliper measurements in a boxplant is not a sensitive quality control method. The medium has a large caliper recovery property, and most of the recovery occurs in less than one minute after crushing. A possible better quality control method would be to measure actual clearances at the pinch points in the boxplant process.

6. The documented adverse effect of low bond strength on the average ECT indicates that the adhesive application systems on the corrugator should be kept in good working order. This includes keeping a uniform adhesive application rate in the cross-machine direction, eliminating glue-station roll run-out problems that will cause machine-direction bond strength cycles, and controlling the adhesive properties and the glue station mechanics to avoid adhesive film defects such as mottle and ringing. TJ

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