Ring crush and short span compression for predicting edgewise compressive strength

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ABSTRACT: We generally use the ring crush test or the short span compressive test to measure the strength of containerboard. Though previous work has attempted to correlate these two tests, once we reduce the impact of basis weight, any correlation is largely lost in the noise. Following that theme, we see that noise plays a very important role in determining which test better predicts combined board performance. The short span compressive test may measure a more fundamental paper property, but due to the level of variability in the material and the testing process, the ring crush test appears to serve as a better predictor of final board and box performance.

Application: This paper addresses some of the confusion present in the industry regarding the correlations between paper strength testing and combined board performance, presenting data which will help readers understand and optimize their approach to predicting container performance from paper properties.

Adequate top-to-bottom compressive strength is one of the primary end-use requirements for corrugated containers. The edgewise compressive strength (as measured by the edgewise compressive test or edge crush test, ECT) of the combined board plays the most important role in overall box compressive performance [1, 2]. Historically, there have been many efforts to correlate the ECT of the combined board with material properties of the containerboard components (the linerboard and medium). Our industry presently relies primarily on two different methods for quantifying the compression strength of the components, the ring crush test (RC, TAPPI T-822) and the more recently developed STFI short span compressive test (STFI, TAPPI T-826), with about half the industry preferring one test and half the industry preferring the other [3]. Yet, neither RC nor STFI are truly independent parameters; both depend on how we operate our papermaking equipment. RC values and STFI values can vary independently for a given grade of paper, either due to noise or due to clear differences in the paper machine processes by which these physical properties are achieved [4-8].

Understanding fundamental material properties and their interactions can be very important when it comes to developing a mechanistic model of box performance. Equally important however is our ability to accurately measure and apply the knowledge gained from those models. There have been numerous attempts in the literature to correlate RC and STFI values to enable conversion from one to the other [9-11], yet we must wonder how they can be correlated given their different underlying mechanisms. RC samples fail by a combination of buckling and compression, much like boxes themselves, while STFI samples fail almost solely by compression [12, 13]. Thus, the physical properties they measure are likely different. Several authors argue that STFI is more appropriate for modeling combined board failure [5, 14-18]. Though empirical equations can be developed to correlate combined board ECT with either test [2, 16, 19], practically speaking the best test is the one that can be most accurately used to reach the end goal of predicting container performance.

This article begins by revisiting the relationship between RC and STFI so often explored in the literature. As noted elsewhere [3], both properties are strongly basis weight dependent, an important fact missed in many other analyses. We present results demonstrating that when exploring balanced data sets, these two tests cannot be statistically correlated in a meaningful fashion beyond their joint dependence on this independent parameter. We then investigate the role of noise in our data collection and the impact of noise on our ability to predict container performance given paper performance.

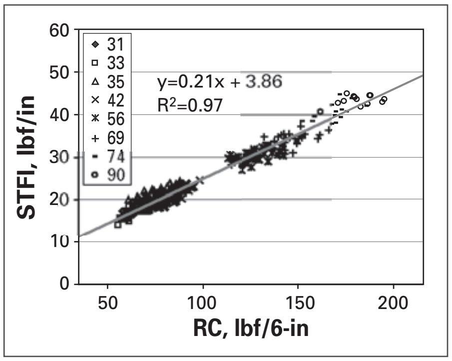
The ring crush and STFI relationship

Figure 1 presents STFI and RC values for more than 300 linerboard samples produced at roughly 20 different mills across the country.[1] We see that over the full range of basis weight, from 31-90 lb/msf (pounds per thousand square feet) or 150-440 g/m^2 linerboard grades, RC and STFI are linearly related with an R^2 value of 0.97, implying that 97% of the STFI value can be accounted for by a linear correlation with RC [20]. We might thus assume, as some approaches do, that we could use the equation presented to convert from one property to the other for any given grade of paper.

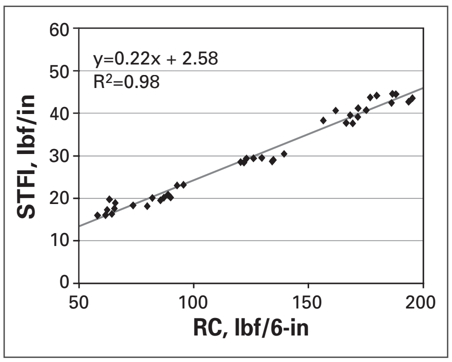
This conclusion is much like concluding that ice cream causes drowning, because both ice cream consumption and drowning rates increase in the summer. Both STFI and RC are directly related to basis weight, and both increase as basis weight increases. Over a large enough basis weight range, we would therefore expect a direct correlation between them. We can highlight the importance of this misunderstanding by focusing on specific basis weight ranges and re-examining the correlation between STFI and RC. For both lower (**Fig. 2**) and higher (**Fig. 3**) basis weights, the best-fit straight line is different from the global correlation, and the R^2 value drops significantly.

Similar to many of the data sets described in the literature, the large data set is not evenly distributed—we have

[1] All physical property test data discussed in this article come from testing at the Materials Testing Lab of Packaging Corporation of America in Mundelein, Illinois, USA. Samples were preconditioned and conditioned according to TAPPI T-402, with samples collected according to TAPPI T-400. Various physical tests were performed according to the relevant TAPPI standards.



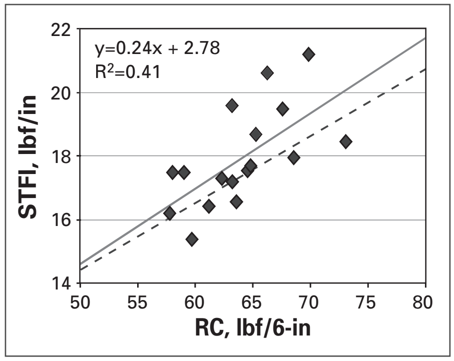
1. STFI vs. RC for a range of papers of different basis weights (lb/msf).



4. STFI vs. RC for papers from one production facility.

significantly more data at lower basis weights than we do at higher weights. This has the effect of giving a fitting routine more flexibility at lower values while forcing it to fit a narrower data set at higher values, potentially leading to dramatically skewed fits [21]. Further, this large agglomeration of data includes papers made with or without recycled content, refined at different levels, and subject to other differences in the papermaking process. Since these differences are not evenly represented, they may also lead to artifacts in fits, or at the least add to the noise in the system. We explored correcting for this potential bias by selecting samples from relatively evenly distributed basis weights, all collected from the same mill. One such subset included linerboard samples from 31, 42, 56, 74, and 90 lb/msf (150, 205, 275, 360, and 440 g/m^2 respectively, **Fig. 4**). The slope, intercept, and R^2 value for this smaller data set are very similar to the overall data set, but we can now see even more clearly that the global fit locally under-predicts some values and over-predicts others. The fitted line has clear systematic deviations.

As we see in Figs. 1-4, once we reduce the impact of basis weight, any correla-

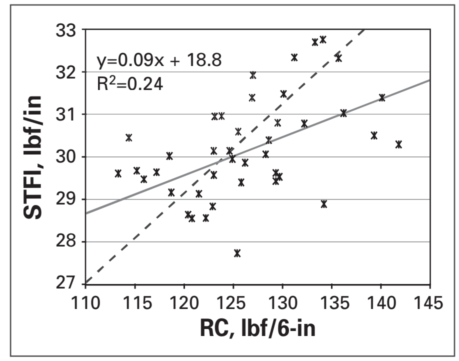


2. STFI vs. RC for 31 lb/msf (150 g/m^2) papers. The global fit is presented as a dashed line, with the solid line representing the best fit to the more limited data set.

tion is largely lost in the noise. Since this implies that the two tests likely cannot be correlated meaningfully beyond their mutual connection to basis weight, how can they both be used to predict box performance? The reason is that box performance is still related to the mass of fiber used in making the box. Mass matters, and over a large basis weight range, it is the dominant factor determining either RC or STFI. However, as exemplified by the statement "we can get RC but not STFI" (or vice versa), other papermaking factors are important as well once we focus in on the narrow basis weight range of a single grade [22]. Our industry would benefit from a statistically designed experiment carrying basic mill process variations for a single basis weight through to their impact on RC and STFI, ECT, and box performance.

Signal-to-noise ratios

Historically, basis weight, RC, and STFI have all been used as predictive measures of the performance of containerboard and containerboard's expected performance in combined board. These three properties have different levels of intrinsic variability or precision with which they can be determined. Variability is important in modeling, since uncertainty in an independent variable in a model will lead to uncertainty in the modeled variable. For instance, if we have a predictive equation y=C*x, an uncertainty in the measurement of x of ±1 will lead to an uncertainty in y of ±C. If we develop a model based on x and y data, uncertainty in the measured values of x and y would lead to a range of possible values for C. Any fitting we would attempt to do would lead to equations



3. STFI vs. RC for 56 lb. papers. The global fit is presented as a dashed line, with the solid line representing the best fit to the more limited data set.

with progressively lower confidence, precision, and utility given increasing variability in x and y.

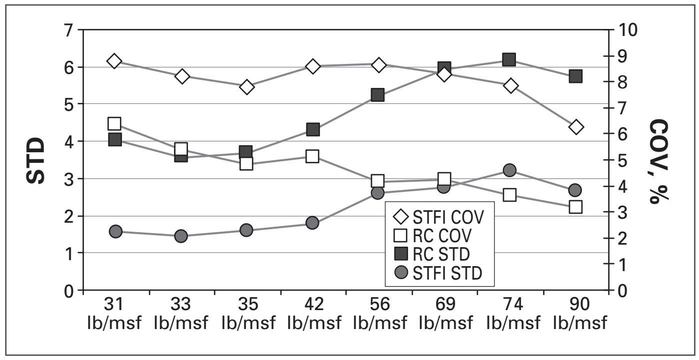
From the same large data set discussed above, we can identify the standard deviation in measurements for basis weight, ring crush, and STFI for various grades, as well as their coefficients of variation (COV) relative to the average of the measurements. (This fractional variation is a measure of the noise to the signal, 10% variation indicates that the uncertainty in the measurement is 10% of the measurement value.) These are similar in magnitude to the data typically reported in the industry-wide collaborative testing program [23]. The COV in basis weight ranges from roughly 0.9% at low weights to 0.6% for higher weight papers. The value of the standard deviation in RC is higher than that in STFI, but the COV is smaller (**Fig. 5**). Both are much larger than for basis weight. Some of the variability measured is due to internal variations in a sample and some to the measurement method and equipment. From the typical standard deviations and COVs, we learn that we can know the basis weight of a sample much more accurately than RC and RC about twice as accurately as STFI. Thus, if each parameter had the same impact on ECT, models to predict ECT based on basis weight might be expected to be more accurate and thus serve as better predictors than those based on RC, and models based on RC might be more accurate than those based on STFI. In the designed experiment data discussed below, we observed similar variability. In an environment in which the variability in testing of basis weight, RC, and STFI are significantly different than typically observed for conditioned samples in a

	BASIS WEIGHT	RC	STFI
R-squared (T839)	0.748	0.852	0.812
Constant	-21.00	8.53	3.42
P1	0.34	0.14	0.54
P2	1.52	0.31	1.36
R-squared (T811)	0.847	0.873	0.666
Constant	-32.04	1.24	-0.05
P1	0.44	0.17	0.53
P2	1.55	0.33	1.40

I. Fitting parameters for the model "ECT = P1 * (sum of liners) + P2 * medium + constant," where the ECT (lb/in) value is modeled based on basis weight (lb/msf), RC (lb/6-in), or STFI (lb/in).

R-SQUARED VALUES	35#-56# liner, 23#-40# medium (n=12) BASIS WEIGHT	RC	STFI
T839 ECT	0.992	0.995	0.994
T811 ECT	0.994	0.997	0.997
Box Compression	0.956	0.954	0.936

II. R^2 values for fits to the same linear model as in Table I. The increasing breadth in the data results in better fits due to a higher signal-to-noise ratio.



5. Average variability by nominal grade basis weight of the RC and STFI tests as summarized from >300 samples presented in Fig. 1.

testing lab (as represented by the results presented above and cited in *Literature Cited* number 23), the conclusions which follow might not be expected to hold.

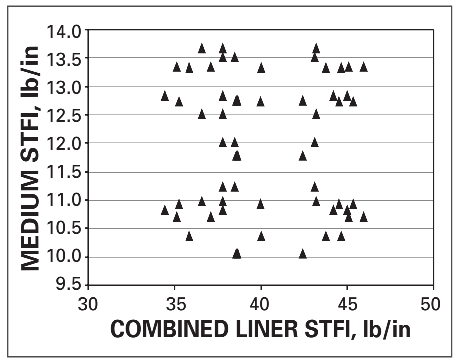
Designed experiments

We probed the impact of these analyses through several designed experiments on different corrugators. Some of these in the lightweight range [31-42 lb/msf linerboard (150-205 g/m^2), 23-26 lb/msf medium (110-130 g/m^2)] can be combined to form a larger, well-balanced data set including 58 different measurement sets for liner and medium properties through to combined board. (**Fig. 6**) By blocking the analysis of this data for machine position and specific experiment (corrugator), we focused in on the impact of paper properties on the combined board ECT. [2]

Following the literature, we modeled the ECT using a linear combination of liner and medium properties. A linear fit model, based on the measurements taken on these papers, has a reasonably low standard error of design, more than adequate precision, and high confidence. Using this type of model, we can predict ECT results from the papers' basis weights, RC values, or STFI values. Modeling with clamp-method ECT (T-839) or wax method ECT (T-811) values from board off the corrugator leads to different fitting coefficients, likely due to differences in the different COVs of each of those tests. (**Table I**).

We can relate the variability of the measurements to the quality of the fits. All fits have R^2 values indicating that they model the data adequately, though some are clearly much better than others. R^2 gives us direct information about the signal-to-noise ratio of the fit itself, and as such R^2 values can be compared between two fits on equally sized data sets to demonstrate which fit more accurately represents the data. The fit for RC is the best, significantly better than the fit for basis weight or STFI. The fact that the basis weight fit is worse than the RC fit, despite knowing basis weight an order of magnitude more accurately than RC, indicates that there is value in the compressive strength measurement beyond its association with the mass of material in the board. In other words, ECT depends on more than just basis weight in ways that we can quantify by using RC. The RC fit is also better than the fit generated when using STFI values, implying that we can use RC to more accurately predict ECT values. This does not mean that RC is necessarily a better measure of the properties associated with box compression, though it may be. Because we can know RC more accurately than we can know STFI, it does indicate that we can build models based on RC with more confidence than we can models based on STFI, at least for the lighter basis weights in the data set explored here.

The range of variation of a property in an experiment is important, as the larger the range the less important uncertainty in individual values becomes. We saw this effect prominently in the difference in slopes in Figs. 1-3. In the combined designed experiments, the basis weight difference between the highest and lowest basis weights explored (the range explored) is about 25 times the variability in basis weight measurements. The RC range is about seven times the variability, while the STFI range is only about three times the variability. We can attribute the distinct difference in the quality of the fits in large part to this difference in signal to noise.



6. Distribution of data points for combined experiments. The STFI of the medium is plotted against the sum of the STFI values of the two liners. Distribution is similar for RC and basis weight. Points are relatively evenly and symmetrically distributed, such that no single point has leverage in the model greater than 1.26 times the average.

[2]Blocking is a statistical technique that removes a potential source of variation from an analysis before the effects of the independent variables of interest are tested for significance against the noise.

When we broaden the range explored for each property, by running designed experiments with wider basis weight distributions in linerboard and medium, the signal-to-noise ratio increases for all three properties (basis weight, RC, and STFI) as does the quality of the corresponding fits. (**Table II**) As we carry the analysis to box compression values, we find RC is still a better predictor of performance. The extra "noise" added through the converting process impacts the STFI correlation more because of the comparatively lower accuracy with which we know those values. Although the signal to noise of the STFI measurement improves, it is still less than half the signal-to-noise ratio of the RC measurement, and so more affected by other sources of variability. This would continue to be the case whenever the COV is higher for STFI than RC. In these situations, RC would likely be more useful as a predictive measure.

CONCLUSIONS

Though ring crush and short span compression have both historically been used to qualify the performance of containerboard and predict its performance in combined board, they do not measure the same property. Previous work has attempted to correlate the two tests, but we have shown that once we take into account the impact of basis weight, the correlation is largely lost in the noise. This noise, or measurement variability, has not generally been considered in literature discussions of these properties, but it significantly influences which test can better predict combined board performance. The short span compressive test may measure a more fundamental paper property, as discussed in the literature. However, as we demonstrated with results from several designed experiments, due to the level of noise in the testing processes themselves, the ring crush test appears to serve as a better predictor of final board performance. **TJ**

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INSIGHTS FROM THE AUTHORS

I recently noticed that the results we were generating in our lab did not agree with much of what I found in the literature. This discrepancy was worth exploring and has led to the current paper. There are a number of literature articles on the benefits of STFI over RC, but none seemed to mesh with the data we were finding (see the intro to the paper.)

This article might help paper manufacturers better understand their customers if they do not presently all refer to the same strength characteristics in specifying product performance. This might also clear up some of the confusion regarding the utility of equations many plants use to go from STFI to RC and back.

I would like to see this work reproduced by others, particularly in a larger designed experiment over a broader range of paper grades. Understanding the way paper machine parameters influence these physical properties also would be useful.

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