# Evaluating hardness and the S-test

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**ABSTRACT:** The corrugated industry typically quantifies crush resistance using the Concora corrugated medium test (CMT) on fluted medium or flat crush on combined board. These tests compress the materials until the point of complete failure of the flutes. Combined board elastically resists crushing forces until a certain point, the hardness of the structure, while additional load causes permanent damage and deformation.

This study investigates how hardness can be measured directly from a load curve collected during CMT (or flat crush) testing and how it varies throughout the North American paper supply. It also explores how hardness correlates with the values obtained from the newly developed S-test. This new test method deserves further study as a potentially more appropriate specification for crush resistance of corrugated medium.

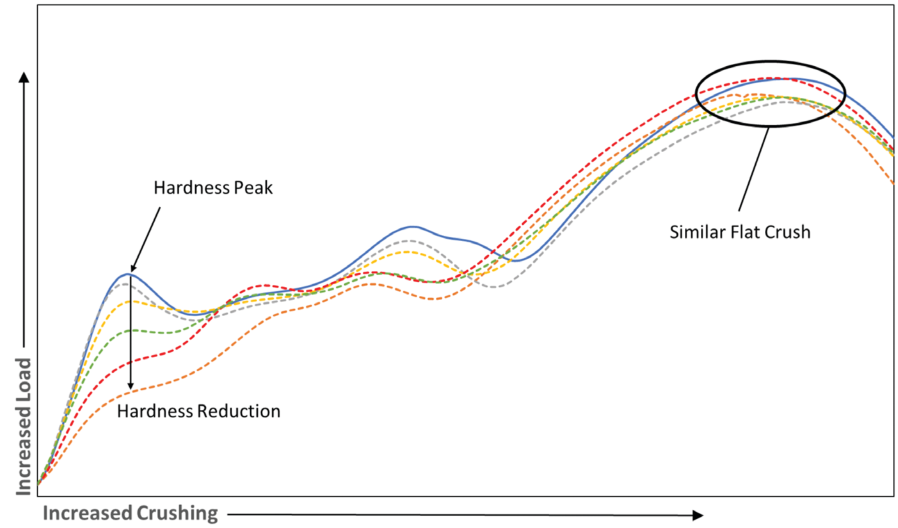
***Application:*** Hardness characterizes the initial loading behavior of fluted medium. Further work studying and standardizing a new approach to evaluating this material property would allow it to serve as a more relevant specification for the crush resistance of corrugated medium.

Box strength comes from board properties, specifically the strength and stiffness of the corrugated board following converting. Board strength comes from paper strength and quality combining, while board stiffness comes from the rigidity of the flute structure and the caliper of the board [1]. One primary manufacturing goal when combining papers on the corrugator is to create robust arches from the medium, in order to maintain the distance between the liners. Much like an I-beam, that separation preserves the stiffness of the combined board, which contributes to achieving higher edge crush (ECT) values and better box performance. Rigid board feels firm to the customer, and more importantly, helps boxes survive longer under load. Once the board is damaged, the flutes feel less rigid and provide notably less structural integrity and long-term durability [2,3]. A manufacturer cannot create a stronger box than the potential present in the paper's inherent strength combined through a high-quality process with minimal material damage.

Current TAPPI Standard Test Methods establish Flat Crush (TAPPI T 825 "Flat crush test of corrugated board: Rigid support method) and the Concora corrugated medium test (CMT) (TAPPI T 809 "Flat crush of corrugating medium: CMT test") as methods used to measure and quantify the rigidity of the medium structure. These tests assess the resistance to pressure in the thickness direction, impacting the ability of a board to be successfully converted without damage and to perform in a customer's automatic setup equipment. Final (test) values from both tests correspond to peak loads in the Z (thickness) direction, occurring when the medium has completely failed, when the fluted structure looks more like mushrooms than arches [4]. By the time that point in the load-deformation relationship is reached, the material is damaged well beyond the point of no return, and the resulting box has been weakened from a performance perspective beyond what is tolerated by the end user. Kellicutt noted as far back as 1959 [5], "…there is little, if any, direct correlation between flat crush values and performance of a corrugated box." Yet, across the industry, medium typically carries a specification for minimum CMT; some combined board may even carry a flat crush specification, particularly by some end users.

Examining the load-deformation curve for combined board during a flat crush test (**Fig. 1**) reveals not only a maximum value, but also one or more intermediate peaks or plateaus. The maximum value indicates the final strength (its flat crush value), while the first peak corresponds to a property called hardness. Though the curves are more complex for board, the paper curves have similar features: an initial ramp up to a first peak, plateau, or inflection point, and then farther out a final peak producing a maximum value.

The loss of transverse shear stiffness from crushing of board during manufacture, particularly from initial compression loading, has attracted attention in recent years. From the existing literature [4,6-11], hardness more appropriately defines the resistance to early-stage compression than the current standardized flat crush (or CMT) method. Combined board reversibly (elastically) resists forces applied in the thickness direction up to the hardness point. Loading beyond that level causes permanent damage and deformation [12], allowing subsequent forces in the thickness direction to induce further damage. Thus, while there is a clear hardness peak in the load-deformation curve for undamaged combined board, damage to the board beyond a certain level (for example, if the feed roll gap on finishing equipment is too tight) reduces or eliminates that peak even while the maximum value (flat crush) remains unchanged (Fig. 1). For cases such as these, it



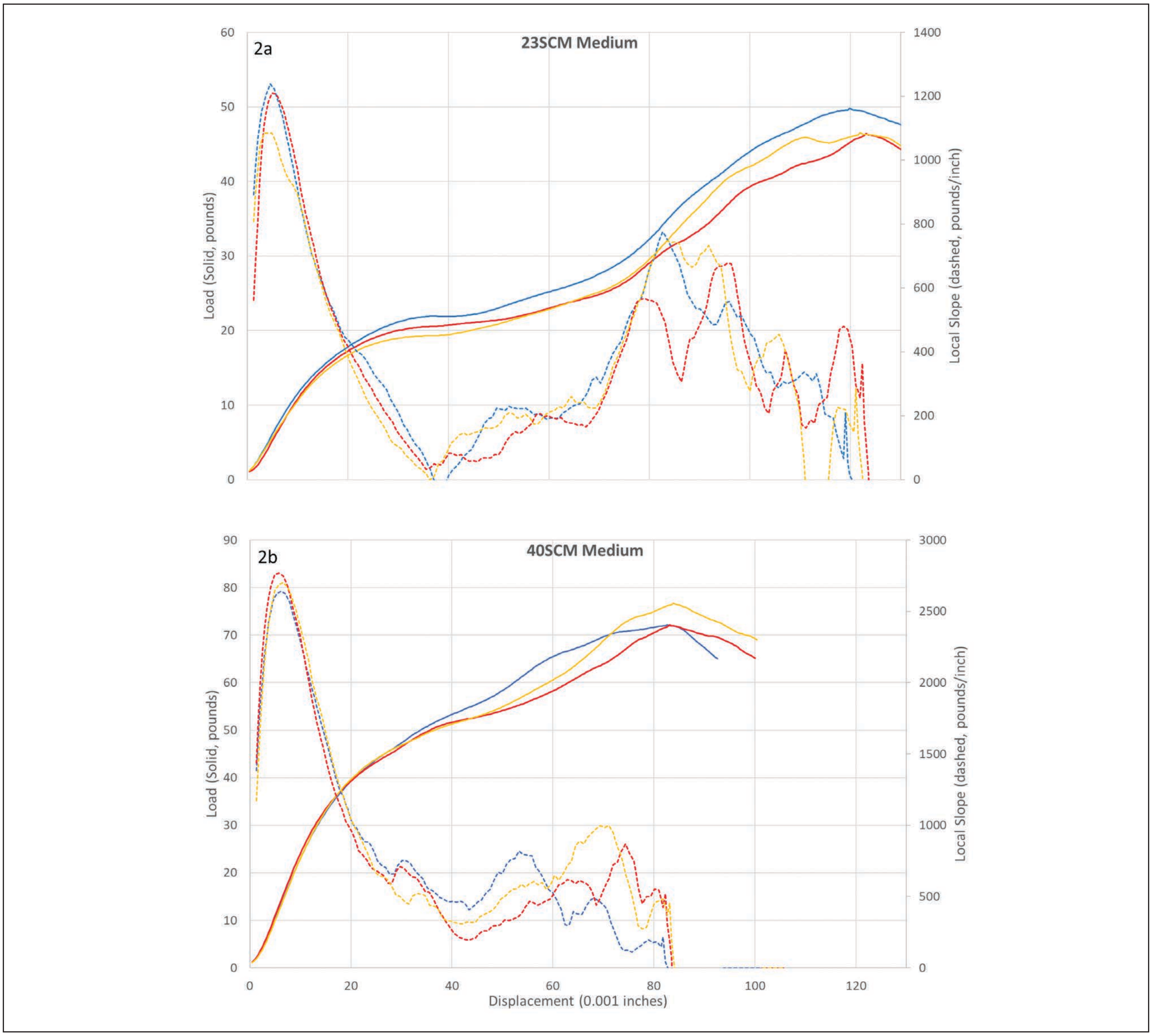

***1. Representative load-deformation curves for C-flute combined board material off the corrugator (solid blue curve) using the flat crush test protocol TAPPI T 825 "Flat crush test of corrugated board: Rigid support method." Dashed curves indicate testing on the same board after it had been subjected to different levels of crushing through the converting process, as applied by the feed roll on a flexo folder gluer. Smaller feed roll gaps apply more pressure to the combined board in the thickness direction, reducing the material's subsequent ability to resist crushing forces. The hardness peak disappears as the board experiences larger crushing forces, even though the rest of the load-deformation curve (and notably the flat crush value) can remain largely unchanged. Each curve represents an average of tests across several specimens collected at a given flexo setting.***

is not possible to automate a process that will terminate the compression test at the hardness point. There is no way to reliably define a yield percentage that will conclude the test at a point that may not be a peak, but instead a plateau or point of inflection (a shift in the deformation process). Recent work by Fürst and Gerards [12] shows that the first plateau (hardness) better correlates with grammage (basis weight) than the maximum load. They also report on an "S-test" that correlates extremely well with the paper hardness value across their sample set of highly recycled lightweight papers. This test can be automated, opening up the possibility of a more rapid and reliable way of obtaining a value that better correlates with a key practical durability property for medium.

This work reviews how one can quantify hardness from a load curve in the CMT test, providing a general definition of hardness that can be applied broadly across papers and combined board using different test approaches. Following this clarification, hardness values for a range of papers of different weights and compositions are explored, emphasizing how hardness varies throughout the North American paper supply. All the results come from work in a single laboratory using a single fluter and compression tester, and while we did not have access to the specific material compositions of each paper collected (furnish type, etc.), we observe consistent property differences between mills. For this same set of papers, the correlation of the S-test with hardness and other properties is examined in order to identify whether this newly developed test could serve as a more relevant specification for corrugating medium.

## MEASURING HARDNESS

A typical load-deformation curve for a fluted sample of lightweight medium has been discussed in the literature. Markstrom [4], Fürst and Gerards [12], and others correlate the features of the load curve with visual images of the shape of the fluting during the loading process. For lightweight medium, there is generally a peak or plateau in the first part of the curve (**Fig. 2a**) that is associated with the hardness value, while the maximum load corresponds to CMT. Of the three specimens presented in Fig. 2a (all from the same sample of material), one has a slope that becomes negative, indicating a true peak in the curve at the first point the slope becomes zero; one has a slope that touches zero indicating a plateau in the load curve; and one has a slope that indicates a shift in the deformation process (an inflection point) without a true peak. Fürst and Gerards convincingly demonstrate that the quality of restraint of the fluted sample defines the shape of the curve in the initial regime. If the CMT test strip has more stable adhesion between the medium and the tape in the test (perhaps using a different tape), the resulting load curves would have more defined peaks in the first part of the curve for each of these strips. The CMT load-deformation curve might then look more like the curve in a flat crush test (Fig. 1). Regardless of how well the paper is fixed, they find the same load/force at the displacement/deformation that leads to the first peak or plateau. That deformation value can be defined by the behavior of the slope: hardness is the load where the slope reaches its first zero or significant minimum. This point is similar for all three specimens in Fig. 2a, and the variation in the load at




***2. Load-deformation curves for two medium grades during the CMT testing process TAPPI T 809 "Flat crush of corrugating medium: CMT test," where increased displacement of the crush tester platens leads to increased deformation of the sample. Both the load curves (solid lines) and the slopes of the curves for the given displacement (dashed lines) are presented for three specimens of each given material. Hardness is defined as the first notable minimum in the slopes. The two sets of curves have the same scale and range in the displacement direction.***

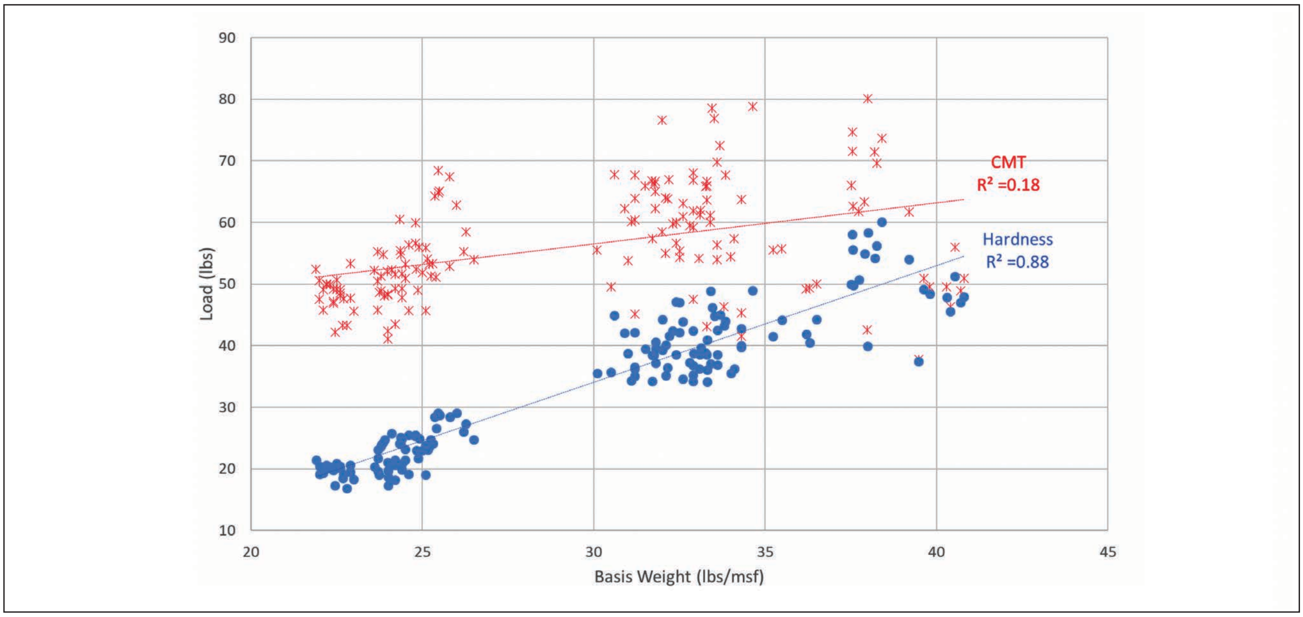
those points gives a measure of the variation in the hardness value given the measurement technique.

While the hardness peak is often clear for lightweight medium, this definition becomes more critical when looking at other mediums. In particular, for heavier, semichemical medium (SCM, Fig. 2b) the overall load-deformation process is shorter—the medium is stiffer and the CMT test reaches its maximum value at a lower displacement of the platens. Once again, the first major shift in the slope defines the point at which the hardness is measured. Hardness for this heavier medium sample occurs at a slightly higher displacement than for the lighter medium discussed, with a higher hardness value. In fact, the value of hardness for the heavier medium in this example is nearly double the hardness for the lighter medium, and it exceeds the CMT value of the lighter medium.

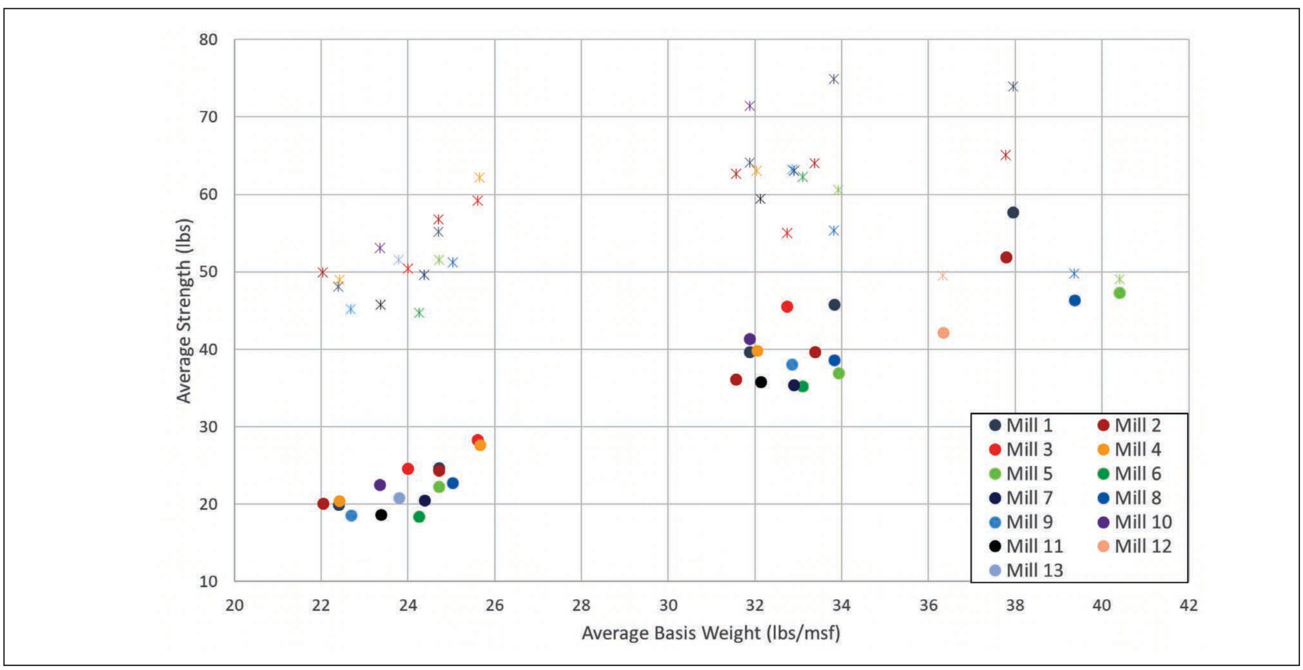
This process of measuring hardness from the change in slope is tedious, and not amenable to rapid assessment (for example, in an automated mill test lab). If there was consistently a true peak at that first point, the "fallback" on most compression equipment could be set to a very small value and automatically capture the moment of the first drop in load and the load at that point. Because there is not always a peak at the hardness point even for light medium, the entire load curve needs to be examined in order to identify the point at which the slope of the curve first meaningfully changes. Most automated mill and lab equipment is not designed to do this.

### CMT AND HARDNESS ACROSS THE NORTH AMERICAN PAPER SUPPLY

As an industry, there are some known challenges measuring CMT on heavyweight medium, including the fact that some medium is more prone to leaning flutes during compression, likely because of fluter settings or paper properties. Some medium seems to collapse more readily after the initial run up in load. As we saw in Fig. 2, the load curve usually looks quite different for heavyweight medium than lightweight medium, either due to the medium behavior in the fluter (initially optimized for 26SCM many decades ago), due to the resistance of the structure to deformation relative to the adhesion of the medium to the tape, or some other factor. Regardless of the root cause, which requires more study to define clearly, the challenge of measuring high CMT values on ostensibly stronger medium should not be surprising to those familiar with the test.




***3. CMT and hardness values for a range of paper samples collected from mills across North America. Each data point represents an average of ten specimens from a given sample.***




***4. CMT (stars) and hardness (filled circles) values, averaged by nominal grade, for papers from 13 different North American medium mills. Color coding is maintained between the hardness and CMT values. Each symbol represents the average of 3–5 (most typically, five) samples of a given grade from the indicated mill. There are at least two different grades represented for most of the mills presented.***

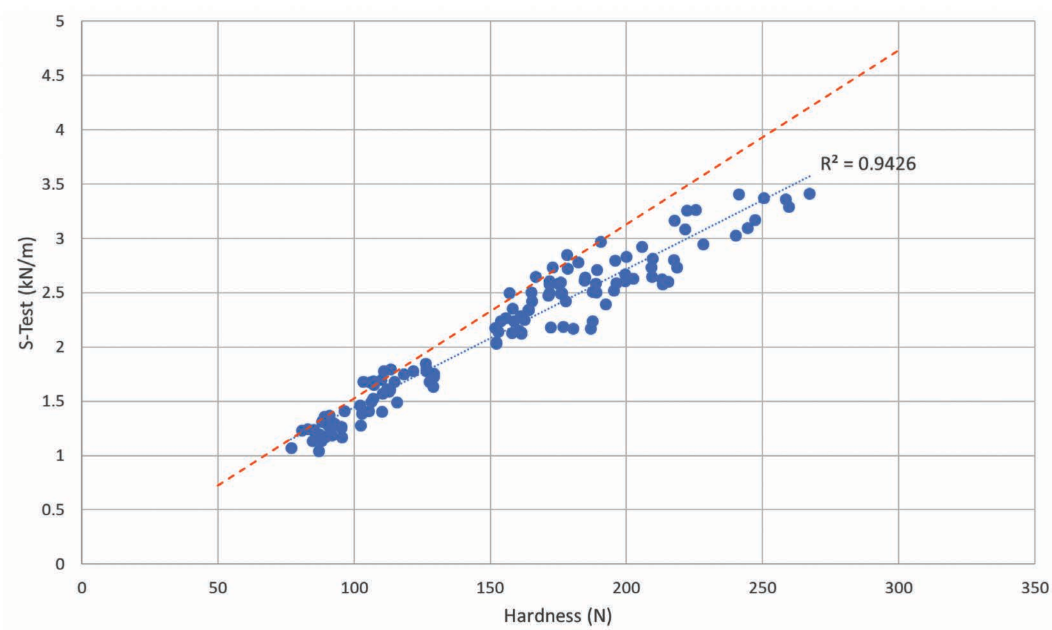
In this study, there were 159 paper samples collected from 13 different paper mills, including traditional semichemical hardwood mills, 100% recycled medium mills, and mills producing medium from softwood pulp. While the prior study [12] primarily or exclusively examined recycled medium in Europe, many of the key observations are similar. CMT correlates poorly with basis weight (**Fig. 3**), which can make it difficult to justify a heavier medium to combined board customers who are concerned about the material's resistance to crush in the thickness direction. Assessing hardness values for the same papers (Fig. 3) by measuring that first peak may lead the customer specifying crushing resistance to be more comfortable with their (generally correct) assumptions broadly connecting weight to strength and improved performance. The initial resistance to crushing forces correlates more strongly with basis weight; the material will have a higher hardness as fiber is added, even if this relationship is not as apparent when comparing CMT and the basis weight of the sample. Shifting our focus to hardness draws a more direct connection with the improved box quality expected when increasing the basis weight of the medium.

Across a broad range of grades, some mills produce papers with higher CMT and higher hardness than others (**Fig. 4**). As weight increases, the gap between hardness and CMT decreases, and for some papers, disappears almost entirely. Whether this is a function of the test methodology or of the materials is unclear, but it is further evidence that hardness is a more consistent assessment than CMT. While this observation has been present in literature for decades on smaller data sets, the challenge has remained as to how to reliably and efficiently assess hardness.

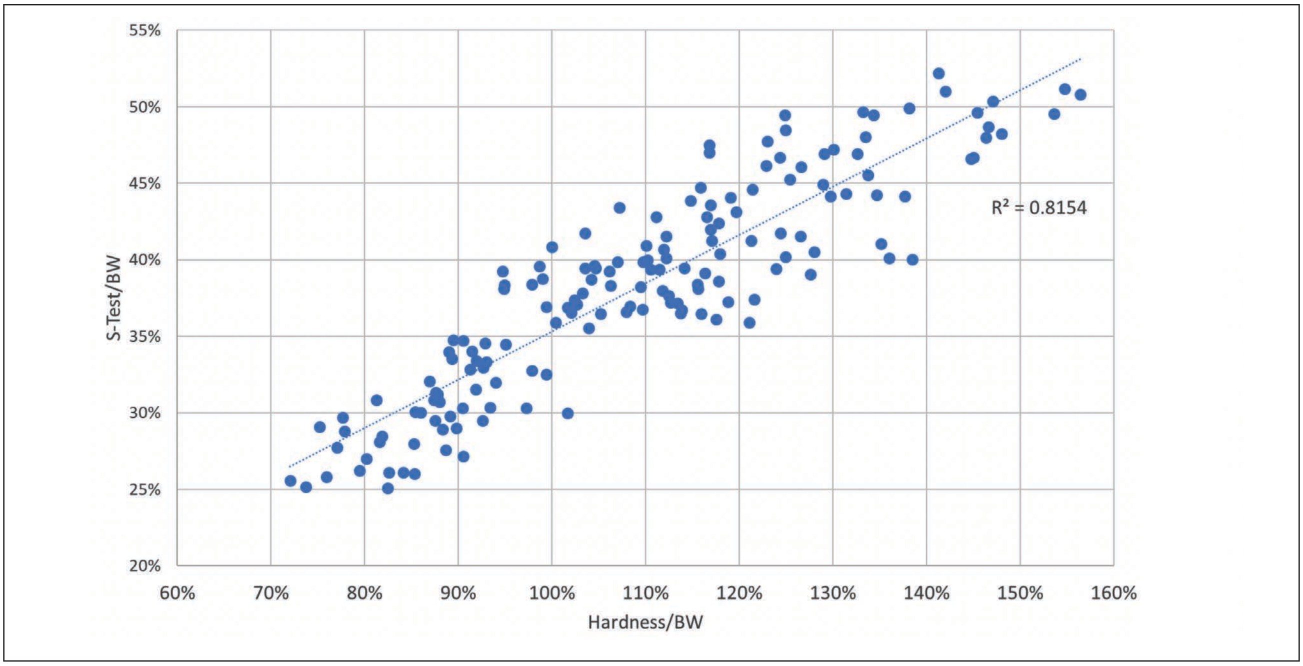
## THE S-TEST

As noted, paper hardness can be time consuming to measure and is not amenable to automated assessment. Fürst and Gerards recently reported on what they call the "S-test" [12], starting with the basic equipment for an SCT measurement (TAPPI T 826 "Short span compressive strength of containerboard," colloquially known as a STFI test) but expanding the amount of material under test and offsetting the clamps. This has the effect of creating an "S" type shape in a section of medium roughly 4 mm in length, similar in structure to half a flute. When the clamps of the equipment then push together, the medium shape buckles, as it (conceptually) might in the initial loading on fluted medium in a CMT test. Buckling causes the resistance of the strip to the applied load to drop, making the measurement of that first buckling easy to automatically measure. It is unclear whether the test parameters used (amount of offset, clamping force and speed, etc.) are optimized or ideal for assessing the underlying material properties, and whether this test truly captures the pure buckling failure of the fluted sample shape. It may mix buckling failure with a compression strength component, as does ring crush (for example) [14]. The results described below contribute to the evaluation of the "S-test" methodology as it exists, providing support for continued development and refinement.

The S-test produces a simple value across a wide range of medium weights and strengths, and that value correlates well (**Fig. 5**) with the hardness of the medium across the full range of grammages examined ($R^2$ >0.94). Each data point corresponds to an average of 20 S-test measurements and 10 hardness measurements on strips from a given medium sample, with the different points coming from each of the papers




***5. Correlation of S-test values with hardness values. Individual data points are presented for the 159 samples in this study, along with the best fit straight line correlating the data. The dashed line is the correlation presented in the prior literature [12]. Each data point represents an average of 20 S-test measurements and hardness values from ten specimens.***




***6. The correlation of the S-test with hardness remains strong even when normalizing for basis weight, confirming that the two measurements rely on similar physical phenomena and are not both increasing simply because strength properties of papers correlate with mass.***

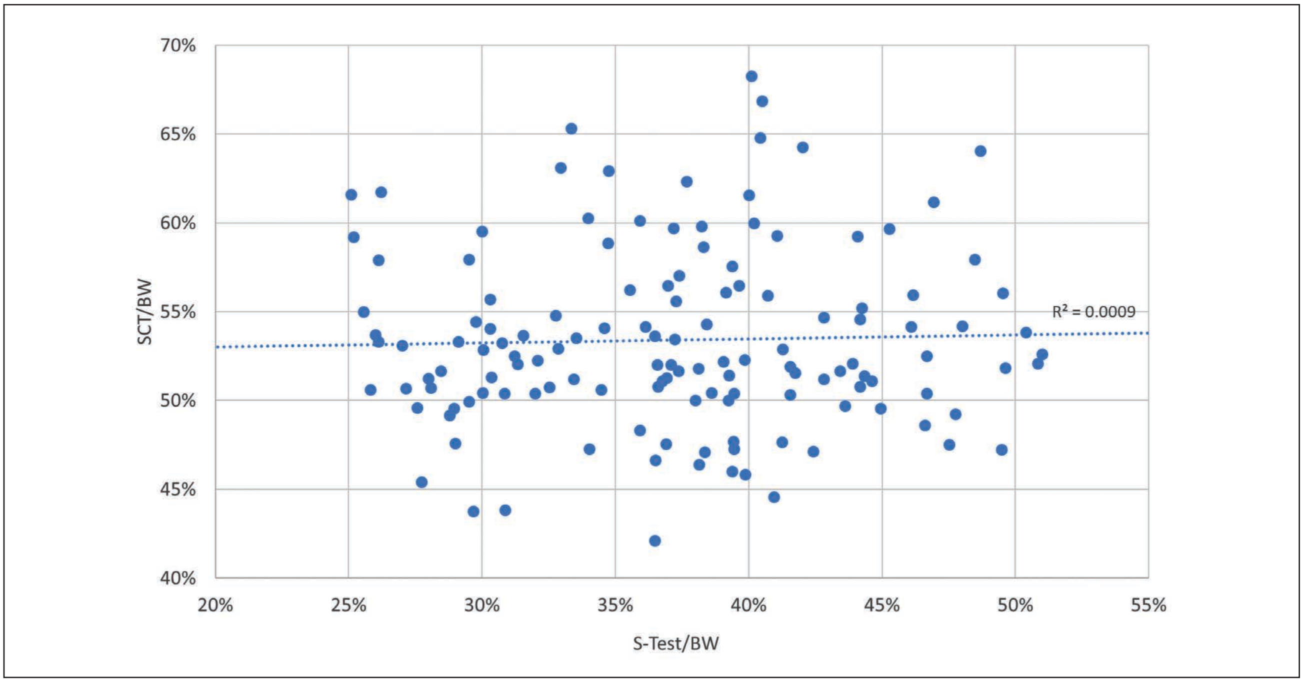
described previously. The correlation remains strong even when we normalize the results against the basis weight **(Fig. 6**). However, much like for other strength property correlations (like ring crush and SCT) [13], the correlation across a wide basis weight range does not actually mean the properties are well correlated locally. If the industry is to use the S-test to assess hardness (as distinct from CMT), it needs to correlate well, not only globally, but also within individual grades or ranges. Examining subsets of the data (**Table I**), we find that the fitting quality of each of those more-local fits is lower than the global $R^2$ as expected from the smaller data sets. Overlapping 95% confidence intervals for the slope between the full data set and both the lightest nominal grade (23SCM) and the heaviest nominal grade (40SCM) examined clearly indicate that the larger fit models the data locally as well. The slope for 33SCM falls close to, but outside, the confidence interval of the main fit, potentially indicating that additional work may be required to define a more appropriate correlation parameter.

Though the equipment for the S-test appears similar to SCT equipment, with similar overall mechanics, the property measured is distinctly different. By compressing paper at a very small length scale (0.7 mm), the SCT measures the pure compression strength of the underlying sheet, directly related to the strength of the individual fibers and the mass of fibers present. This value is completely uncorrelated with the S-test value (**Fig. 7**) once we control for basis weight, confirming that the S-test assesses the buckling resistance inherent in the first part of the load-deformation curve independent of the compressive strength of the fibers themselves.

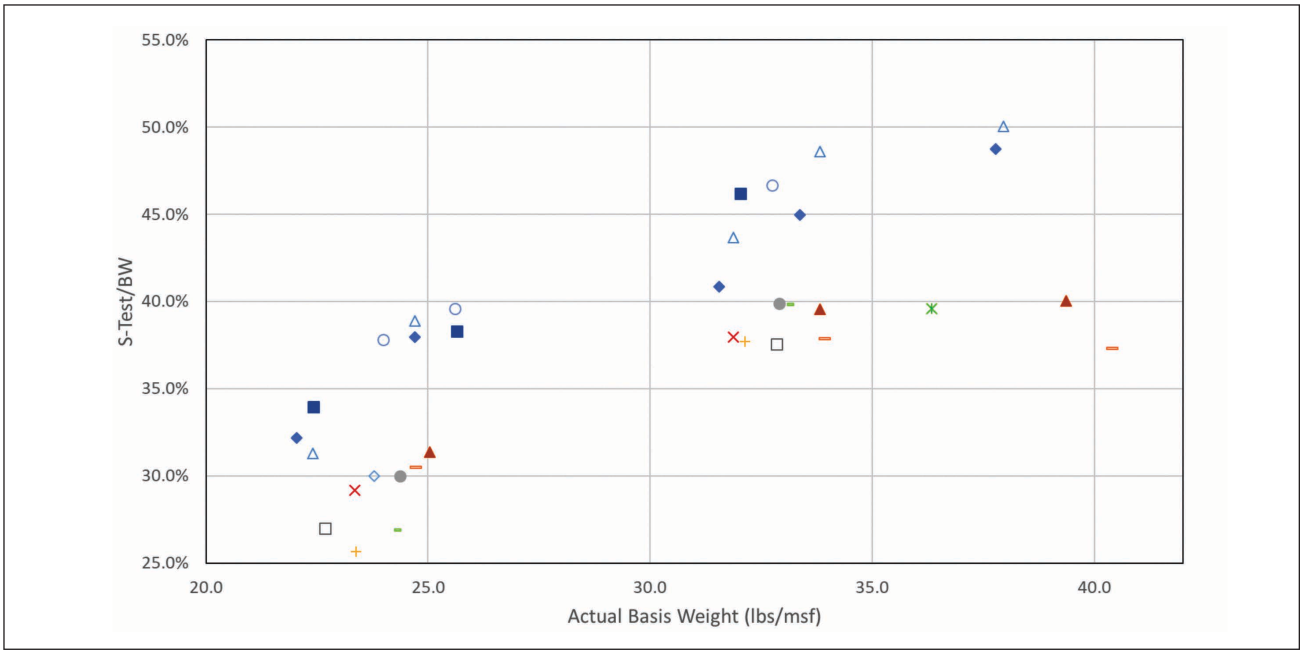
The correlation between the S-test and hardness reported here does not quite follow the data found in the prior literature (red dashed line in Fig. 5), potentially because the fiber furnish and paper types are notably different between the two

| | | | Intercept, lbs/in | | Slope, lbs/in per lbs | | | |
|---|---|---|---|---|---|---|---|---|
| Data Set | n= | Rsq | Mean | St. Error | Mean | St. Error | Lower 95.0% | Upper 95.0% |
| All materials | 159 | 0.943 | 0.65 | 0.23 | 0.329 | 0.006 | 0.317 | 0.342 |
| 23SCM | 54 | 0.657 | 0.34 | 0.69 | 0.331 | 0.033 | 0.264 | 0.397 |
| 33SCM | 44 | 0.514 | 4.15 | 1.42 | 0.242 | 0.036 | 0.169 | 0.316 |
| 40SCM | 20 | 0.692 | 3.41 | 2.16 | 0.268 | 0.042 | 0.180 | 0.357 |

***I. Regression parameters fitting S-test values to hardness values across the full basis weight range as well as for subsets of the data based on nominal paper grade. For these fits, S-test was measured in pounds per inch and hardness was measured in pounds.***




***7. When normalized for basis weight, we see no meaningful correlation between SCT and the S-test. These two measurements assess inherently different physical properties.***




***8. Each unique combination of shape and fill represents one of 13 North American medium mills and their respective S-test efficiency. Some mills achieve notably more hardness/S-test strength per pound of fiber than others, which may account for differences in correlations between test results examining papers from different mill sources.***

studies, or because of inter-lab differences in equipment or methodology. There is evidence in this work that different mills have different efficiencies in their achievement of S-test strength (and hardness as obtained through load-curve examination) at a given basis weight (**Fig. 8**). Thus, while the overall correlation of the S-test with hardness appears to be strong, it is clear that this area requires further examination, and highlights the importance of a broad repeatability and reproducibility study in the development of a formal test method to assess hardness.

To assess the true value of this new test, we must also consider variation within different evaluation methods. The S-test applies load to roughly half a flute worth of material, while the CMT test simultaneously applies load to ten flutes. A single

| Property | Average COV |
|---|---|
| CMT | 5.8% |
| Hardness | 5.9% |
| S-test | 10.0% |

***II. Average level of variation in test values across the 159 papers examined, expressed as coefficient of variation (COV), the standard deviation divided by the average value. For each paper material, 10 specimens were tested to assess Concora corrugated medium test (CMT) and hardness values, and 20 measurements were made to assess S-test values.***

hardness measurement (from a CMT curve) effectively averages the values of 20 individual S-tests, so we might expect a much higher variability for the S-test than we do for our hardness measurements. Our data agrees with this expectation. Across our data set, the COV (the standard deviation divided by the average) of our S-test results was nearly twice the COV of our hardness measurements (similar to difference in measured variation found when comparing SCT and ring crush). This occurs despite the S-test averages having twice as many measured values (**Table II**), and in spite of the fact that hardness measurement can have notable sources of contributing variation, as discussed previously. This provides a caution regarding the S-test itself. Though this method may be able to make the measurement more rapidly, it comes at the cost of additional uncertainty in the value measured. This may have significant impact if we use the S-test value for subsequent modeling, since no estimation model can be more accurate than the uncertainty in the model's input parameters. However, given the lack of methods to quickly and easily assess this property, further work to understand the robustness of the approach and develop a formal test method is strongly encouraged.

## CONCLUSION

Though hardness is well established in the literature as the property of fluted medium that is best related to its initial loading behavior, it finds little use in industry because of the challenges inherent in rapidly measuring it. While the hardness value can be determined from analyzing the slope of a load-deformation curve, even when there is no pure peak in the curve itself, it is difficult to determine this value in automated test equipment because of the lack of a consistent behavior in the curve at this point. The recently introduced S-test assesses the buckling resistance in the first part of the load-deformation relationship, which correlates well with the hardness of the board across a wide range of papers. Additional work may be required to refine testing parameters to ensure isolation of a "pure" buckling mode. Though the S-test allows for an automatable measurement, it comes at the cost of additional uncertainty when compared to the method where hardness is identified from the slope. This inherent variation in the test method may impact the S-test's utility, but given the lack of formalized test methodologies to assess hardness, further work to understand the S-test and develop an official test method is strongly encouraged. **TJ**

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We chose to study the S-test because it is an interesting new test and addresses an area of importance to corrugating and converting practices. This work builds on and expands other work in the literature, most recently that reported at a 2017 conference.

The most difficult aspect of this work was building the correlations with manual assessments of the data curves. Interestingly, we found that there can be a notable difference in properties between mills. This is worth further exploration to assess root causes.

For mills, this study provides insight into a potentially better way to measure a key physical property for corrugating medium and corrugating board. The next step is to correlate these values with real-world end properties in a statistically meaningful way.

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