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Relationship between the ECT-strength of corrugated board and the compression strength of liner and fluting medium papers

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Executive Summary

The compression strength of any corrugated board box is a direct measure of its stacking strength. The compression strength of a box is measured according to a standardized test method known as the Box Crush Test. Numerous studies, initiated from the basic work conducted by McKee and Gander (1962), have been published indicating which properties of the corrugated board give the corrugated board box its compression strength. Further this was extended to studies investigating, which properties of the substrates (papers) are critical to achieve desired strength corrugated board. It was therefore the primary aim of this research to establish predictive mathematical correlations between corrugated board and paper compression properties, which can be used in the South African corrugating industry.

The relationship between the corrugated board edgewise compression strength (ECT) and its components' characteristics can be analyzed in many ways. Some of the reported in literature relationships between paper and board properties have become progressively more complex as the models have been refined to take into account all of the important structural and component characteristics. These models can be used for detailed research and development purposes, but they are too complicated for practical use. A more useful approach to predict the compression strength of the corrugated board is to sum the compressive strengths of the linerboards and medium making up the corrugated board, allowing for the draw of the medium (Maltenfort model). This approach gives good predictive accuracies, if based on appropriate statistical weighting factors. It is also necessary to select adequate and practical paper and board compression strength test methods.

The two most widely used paper compression strength test methods in the industry are the Ring crush test (RCT) and the STFI Short-span compression test (SCT). Certain limitations regarding the Ring crush testing method exist, pointing out that this method does not measure the true intrinsic edgewise compressive strength. Preferences were given in literature to the use of the STFI Short-span compression test. The FPL Neck-Down test method resembles best the failure of the corrugated

board under pure compression, but this method is somewhat difficult to be used in manufacturing environment and commercially available equipment for sample preparation is limited. Therefore the more user-friendly and widely spread FEFCO No. 8 (ISO 3037:1994(E)) method was utilized in this investigation, knowing its limitations.

As boxes are generally transported at different climatic conditions stacked on top of each other, when environmental conditions change, the compression strength of the boxes changes. A corrugated box loses half or more of its short-term top load box compression strength when the relative humidity is increased from 50 to 90%. The reduction in compression strength of paper, board and the final box product are correlated, but the magnitude of the reduction is dependent on the testing methodology employed. The major factor affecting the stacking performance of corrugated containers is the moisture content of the board. The equilibrium moisture content of paper is dependent on the ambient temperature and relative humidity among other factors. As moisture content increases, ultimate paper strength properties are reduced, due to a reduction in inter-fiber bonding.

The experimental work conducted in this investigation and the results generated were used to determine the linear regression constants in the Maltenfort model, correlating the measured ECT with the predicted ECT, using the paper components' compression strengths, measured using the SCT and RCT methods. The obtained predictive mathematical models are as follows:

$$\mathbf{ECT = 0.6982\,(SCT_{L1} + SCT_{L2} + SCT_{L3} + \alpha_1 SCT_{F1} + \alpha_2 SCT_{F2})}$$
$$\mathbf{R^2_{SCT} = 0.9758}$$

$$\mathbf{ECT = 1.028\,(RCT_{L1} + RCT_{L2} + RCT_{L3} + \alpha_1 RCT_{F1} + \alpha_2 RCT_{F2})}$$
$$\mathbf{R^2_{RCT} = 0.9625}$$

where the ECT, SCT and RCT are in kN/m, the correlating constant (***k***) is dimensionless and α is the profile and plant specific flute take up factor. The models show very high coefficients of determination, which confirms that they can be used successfully to predict the compression strength of corrugated board using

the measured paper compression strength (SCT and RCT) after exposure to any constant climatic condition.

It was also of interest for this study to determine whether the models obtained for the participating corrugating plants differ. The results indicated that the plant specific predictive mathematical models compared well to the overall linear models and that no major difference exists between the plants' capabilities to convert the paper compression strength into corrugated board edgewise crush strength. These results suggested that a single set of predictive mathematical models can be utilized with good degree of confidence in the South African corrugating industry.

Even though somewhat higher correlation when using SCT results was obtained, the comparative results between the two methods in this study could only confirm that good correlations with the boards' ECT results exist, regardless of the paper testing method used. The linear correlation between the SCT and RCT results obtained in this study, suggested somewhat limited correlation between the results of the two test methods:

$$\mathbf{SCT = 1.3089 \times RCT + 0.2758}$$
$$\mathbf{R^2 = 0.9166}$$

The results in this study also showed that the reduction in compression strength after exposure to the same conditions is different for different papers, but the combined effect of the board's components is reflected in the board's ECT reduction. It was speculated that the difference in strength reduction after exposure to high humidity could be somewhat related to the different paper grades and their furnish composition. In general high performance virgin linerboards and semi-chemical fluting papers showed lower reduction in SCT and RCT after exposure to high humidity conditions. However, these observations suggest the need to conduct further research in this area in order to investigate the fundamentals behind these findings.

KEYWORDS: Paper compression strength, SCT, RCT, corrugated board, edgewise compression strength, ECT, relative humidity

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1. Introduction

As indicted by Markstrom (1999), the compression strength of any corrugated board box is a direct measure of its stacking strength. The author also points that the box compression strength constitutes a general measure of the performance potential of a corrugated board package. The compression strength is measured according to a standardized test method and is in general designated the BCT (Box Compression Strength) value. Markstrom (1999) also warns that only 20-35% of the measured BCT compression strength can be used reliably. Therefore safety factors of between 3-5 times are always required. Even higher factors should be employed where the packages are subject to several reloadings during transportation and long storage times at changing climatic conditions.

However, McKee, Gander and Wachuta (1961) emphasized that the laboratory box compression test is of limited utility for several reasons:

- During production of boxes, a considerable quantity may be manufactured before it is known whether they meet the required strength specifications
- Testing of ready boxes increases the cost of the test and in some instances may exceed the capacity of the testing equipment
- The test is generally not capable of distinguishing between the several factors which contribute to box strength and in a case of inadequate box strength, it may not be apparent whether the fault lies with the component liners or corrugating medium, or the manufacture of the corrugated board, or the conversion operations
- The box test is also so remote in time (and often location) from the manufacture of paperboard and corrugated board as to be of only limited value in the operations of the paper mill and corrugating plant

These limitations led to numerous studies, initiated from the work conducted by McKee and Gander (1962), investigating which properties of the corrugated board give the corrugated board box its compression strength. Further this was extended to studies investigating, which properties of the substrates (papers) are critical to achieve desired strength corrugated board. This research enabled testing and evaluation of paperboard materials in terms of those properties which are of direct importance to the performance of the box.

It is therefore the aim of this research to provide predictive mathematical models to the South African corrugating industry, correlating the measured compression strength of corrugated board and its paper components, using standard testing methods. This would allow packaging technologists in the field to select adequate paper substrates, with certain strength characteristics, to manufacture corrugated board with the necessary compression strength for achieving a desired carton performance for certain climatic condition. Further, the study should establish whether currently used paper compression strength testing methods for quality control and assurance are in alignment with the end-users' requirements for sufficient box stacking strength.

Boxes are being transported at different climatic conditions stacked on top of each other. When environmental conditions change as the goods are transported to different geographical locations, the compression strength of the boxes changes. If the strength is reduced, this would cause undesired collapse of the stack and possible product damage. It is therefore important to determine whether paper properties evaluations at different conditions could be correlated using mathematical models to predict corrugated board performance, which would consequently be transferred to performance of the box manufactured from these combinations of paper boards.

The scope of this study includes:

- A comprehensive literature review on the topic;
- A review of the available paper and board compression test methods used in the industry;
- Conducting a large number of paper combination compression strength evaluations using the two most often utilized paper compression test methods – STFI Short-span compression test (**SCT**) and Ring crush test (**RCT**), after sufficient conditioning to standard and high relative humidity at 23ºC;
- Correlating the paper compression test results obtained, with the compression performance of the manufactured from these paper combinations boards in

terms of Edgewise crush test (**ECT**), using the FEFCO (No. 8) standard method, after sufficient exposure to certain climatic conditions;

- Developing mathematical correlations between the paper and boards compression strength at the different conditions;
- Comparison of the models obtained for the different corrugating plants participating in the study;

2. Literature Review

2.1. Paper properties related to box stacking strength

2.1.1. Box compression strength

In the early 1920s, Rule 41 was introduced in the USA by the shipping industry to establish liability for goods damaged during rail shipment (Gutmann, Nelson & Yerke, 1993). If goods were shipped in a box which met Rule 41 specifications and were damaged, the railway carrier was liable. If the box did not conform to Rule 41, the shipper was liable. Under this original Rule 41, the most important requirement for the box was that it contains and protects the shipped goods. The container materials were designed primarily for bursting and puncture resistance. In recent years, these parameters have lost some of their significance because of the utilization of palletization, and stacking of the containerized purchased goods. This often leads to the collapse of the bottom boxes and damage to their contents. To evaluate the resistance of the containers against this type of damage, the box crush test (BCT) for the manufactured box was introduced and accepted by many manufacturers. These trends led to the revision of Rule 41 for USA rail shipment on January 26, 1991, and Item 222 for the USA trucking industry on March 30, 1991, to support the modern needs of the shipping industry. These regulations now focus predominantly on stacking strength and puncture resistance.

It is well known that a corrugated box subjected to warehouse stacking will support for a prolonged period only a relatively small fraction of the box compression strength as determined by a laboratory box compression test (Whitsitt, Gander & McKee, 1967). Therefore as indicated by Markstrom (1999) only 20-35% of the measured short-term box compression strength can be used reliably and safety factors of between 3-5 times are always required. The differences in box stacking life depend in part on the perimeter of the box, as well as on the combined board edgewise compression strength (ECT) and flexural rigidity. In general, the higher the edgewise compression strength and flexural rigidity of the board, the higher the box stacking strength.

As discussed by McKee *et al.* (1961), during the top-to-bottom compression of the majority of conventional, vertical flute, corrugated boxes, as the applied load is progressively increased, a load level is eventually reached where the side and end panels of the box become unstable and deflect laterally. Having become unstable, the central region of each panel suffers an appreciable decrease in its ability to accept further increase in load and the box will usually bow outward or inward, provided the box is not extremely short. The bending of the panels limits their load-carrying ability over the central region of each panel. However, the portions of the panel adjacent to the vertical edges, remain essentially plane and, therefore are capable of resisting higher load intensity. These differences in load-carrying ability across a box panel are illustrated in Figure 1 in terms of an idealized load profile around the box perimeter.

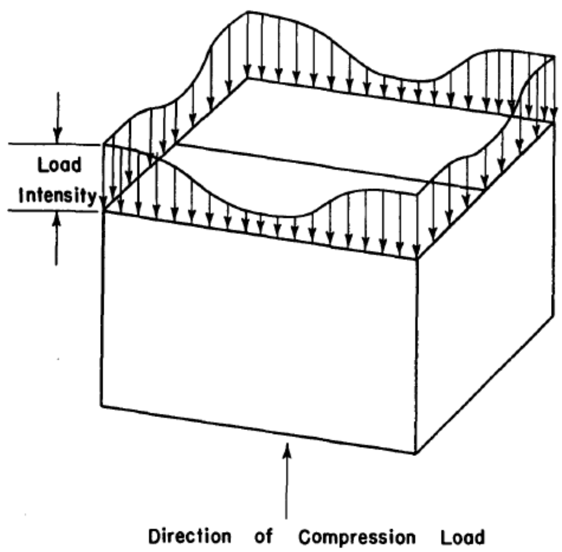


Figure 1. Distribution of compression load around the perimeter of a box (McKee *et al.*, 1961)

The authors further indicated that the box reaches its maximum load when the combined board at or near a corner of a panel ruptures. Thus, the top load strength of a container resides in large part in the combined board near the vertical edges of the box panels in the sense that the edges carry the greatest intensity of load, and rupture of the board at this location triggers failure of the entire box. It was presumed that the material near the edges fails at a load intensity equal or related to the intrinsic compression strength of the corrugated board. It should be noted, however, that the centermost portions of the panel make a significant contribution to the total box load.

The top-load box compression strength is adequately expressed by the equation (1), developed by McKee and Gander (1962):

$$\mathbf{P = 1.97.P_m^{0.753}.sqrt(D_x.D_y)^{0.247}.Z^{0.506}, \text{ when } {}^{d}/_{z}>0.143} \qquad \mathbf{(1)}$$

where:

P = box load [N]

$\mathbf{P_m}$ = edgewise compression strength per unit width of combined board in cross-machine direction (wax-dip short column) – ECT, [N/m]

$\mathbf{D_x}$ = flexural stiffness per unit width of combined board in machine direction (MD) (four-point beam), [Nm]

$\mathbf{D_y}$ = flexural stiffness per unit width of combined board in cross-machine direction (CD) (four-point beam), [Nm]

Z = compression perimeter of the box, [m]

d = depth of the box, [m]

This formula indicates that the ECT of the combined board is a dominant factor in top-load box compression strength. A percent increase in ECT-strength is expected to contribute about three times greater increase in box compression strength (BCT) as would the same percent increase in flexural stiffness and about 1-1/2 times the same percent increase in box perimeter.

The BCT-method is generally acknowledged to be the best representation to practical stacking strength of corrugated board boxes (Markstrom, 1999). The method is pure top-to-bottom short-term load test, carried out on empty sealed corrugated board boxes. These boxes are compressed between flat parallel plates in a compression tester at constant compression rate. The force and strain are continuously recorded until failure occurs. A number of standard test methods for conducting BCT measurements are available, such as FEFCO (No. 50) and TAPPI T804. The maximum load and deflection at failure are reported as BCT results. The standard methods indicate that the test is conducted in a controlled environment of 50%RH at 23ºC.

As the corrugated box subjected to storage stacking will support only a fraction of its short-term box compression strength for a prolonged period of time, a series of studies by Whitsitt, Gander and McKee (1967&1968) were carried out, to provide information relative to the stacking (creep) behavior of corrugated board and boxes. In these investigations the deflection and time-to-failure of top-loaded empty boxes were evaluated for a number of applied load levels expressed as a percentage of their short-term compression strength (BCT). Even though large and statistically significant differences in stacking life were reported by the authors, they found that:

- For the single-wall boxes the best multiple correlations obtained with all factors statistically significant were as follows:

$$\mathbf{log(t) = 8.4762 - 9.81R - 0.0155Z + 0.0105P_m} \qquad \mathbf{(2)}$$

$$\mathbf{log(t) = 8.5255 - 9.47R - 0.0165Z + 0.00262sqrt(D_x.D_y)} \qquad \mathbf{(3)}$$

where

t = box stacking time, [days]

R = applied load ratio – (applied load/BCT)

Z = box perimeter, [in]

$\mathbf{P_m}$ = cross-machine combined board edgewise compression - ECT, [lb/in]

$\mathbf{D_x}$ = flexural stiffness per unit width of combined board in machine direction (MD) (four-point beam), [lb/in]

$\mathbf{D_y}$ = flexural stiffness per unit width of combined board in cross-machine direction (CD) (four-point beam), [lb/in]

The above reported findings indicated that box stacking life increases as perimeter decreases, and ECT and board flexural stiffness increase. These equations explained about 64% of the experimental variance in their studies, thus the authors indicated that further studies are necessary to determine the unexplained variance. They suggested that these variances are probably associated with the large variability in box creep life within a given box sample, as well as other factors such as boxes fabrication quality, differences in creep behavior of the facings and mediums, etc.

- When single- and double-wall boxes were considered in their investigations, the following regression equation (4) was reported with the best multiple correlation with all factors statistically significant:

$$\log(t) = 9.6862 - 10.68R - 0.0173Z \qquad (4)$$

where the symbols are as defined above. In this case, only Z and R were significant factors.

According to Markstrom (1999), McKee's equation (1) probably does not give a complete answer to how the BCT-value depends on the corrugated board properties. He suggested that deviations, mainly due to manufacturing variations and processing equipment may occur. However, the equation (1) can be used and the relationship is valid for statistically guaranteed number of boxes of different sizes, manufactured from different corrugated board grades.

2.1.2. Correlation between corrugated board and its components' properties

2.1.2.1. Corrugated board flexural stiffness

A study conducted by Jonson and Ponton (1984) indicates the importance of not underestimating the corrugated board flexural rigidity in achieving good BCT. However, as the scope of the current study is limited to board and paper compression properties correlation, the discussion of paper properties contributing to good board flexural stiffness will be limited.

In general as shown by Jonson and Ponton (1984), the liners in the corrugated boards are needed to provide the necessary flexural rigidity. The fluting is necessary to keep the liners apart. Failure of the combined board at the vertical edges in edgewise compression initiates box failure and accounts for the importance of edgewise compression strength, as discussed already in 2.1.1. However, the central region of each panel makes a significant contribution to the total box load. Inasmuch as the behavior of these central regions reflects the bending characteristics of the combined board, the analysis of box compression strength involves consideration of the flexural stiffness of corrugated board. Flexural stiffness is the capacity of a structural member to resist bending. In terms of a simple beam, flexural stiffness is essentially the ratio of load to the deflection produced by the load. The greater the flexural stiffness, the greater is the load required to produce a given deflection, as investigated by McKee, Gander and Wachuta (1962).

The combined board flexural stiffness in each direction is estimated by summing the products of the elastic modulus of each component times its moment of inertia relative to the neutral axis of the combined board, as widely discussed by Kellicutt (1961), Koning and Moody (1971), and McKee *et al.* (1962). As a good approximation, combined board stiffness is equal to $\mathbf{EtH^2/2}$ for a balanced constructed board, where **E** is the elastic modulus of the liners, **t** is liner thickness, and **H** is the combined board caliper (McKee *et al.*,1962). Thus, papermaking factors which increase *E* in the appropriate direction of the liners and also their thickness, will increase the combined board stiffness in that direction.

Combined board flexural stiffness is sensitive to the caliper of the combined board. Thus, it is necessary to avoid crushing the board during conversion (Whitsitt, 1988). The critical papermaking factors for the production of a good fluting grade should be focused on achieving paper properties necessary to maintain maximum board caliper for a selected fluting profile, i.e. the most important task of the fluting medium in the corrugated board is to separate the two liners. The Corrugated Medium Test (**CMT**), carried out on the fluting medium alone, is therefore considered to be one of the most important quality properties of fluting material (Markstrom, 1999).

2.1.2.2. Corrugated board edgewise compression strength

The relationship between the corrugated board edgewise compression strength and its component characteristics has been analyzed in two main ways as reported by Whitsitt (1988). In the first approach, the author commented that combined board is treated as a structure comprised of narrow flat plate elements of liner between flute tops and flat or curved plates of medium as shown in figure 2.

These miniature plate elements could become unstable and buckle in the same way that a box panel buckles in top load compression. When such local buckling occurs, the combined board ECT could be dependent on the edgewise compression and bending properties of the liners and medium. Then ECT may be analyzed using the same approach as used in developing the McKee box formula (The Institute of Paper Chemistry, 1963a). In this approach the compressive failure of each miniature plate element will depend on the edgewise compressive strength and bending stiffness of the liner or medium element. Then the ECT strength equals the sum of the liner and medium miniature plate element compressive strengths.

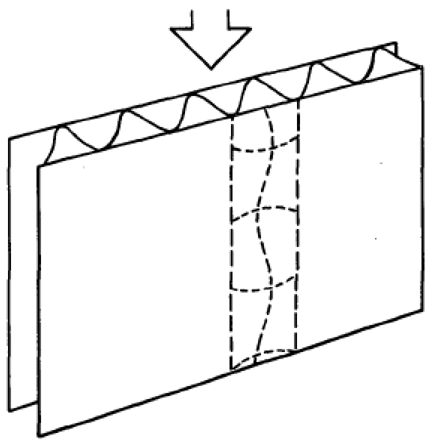


Figure 2. Corrugated board showing component plate elements (Whitsitt, 1988)

Recent work conducted by Popil, Coffin and Kaewmanee (2004) at the Institute of Paper Science and Technology has followed the above approach by investigated the influence of linerboard bending stiffness and interflute buckling on ECT performance. By reviewing data generated in previous reports (Whitsitt, 1988), it was shown that the relationship between ECT and basis weight was weak, that paper compression strength measured by the Short-span compression test (SCT) method was a much better predictor of ECT, and that paper compression strength measured by the Ring crush test (RCT) method had a slightly higher correlation to ECT than SCT. The best results, however, were obtained by using the SCT method in combination with bending stiffness and applying the following equation (5) for predicting ECT:

$$\mathbf{ECT = k\,(2x\sigma SCT_{Liner})^{b}\;x\;[sqrt(D_{MD}D_{CD})/b_f^{2}]^{1-b} + \alpha SCT_{Fluting}} \qquad \mathbf{(5)}$$

Where **SCT** is the compression strength results of the liners and fluting medium papers used for the construction of the board, measured using the short-span compression paper test. The geometrical mean of the liners' bending stiffness in MD and CD is included as the square root of $\mathbf{D_{MD}D_{CD}}$ and it represents the flexural rigidity of the plate. $\mathbf{b_f}$ is the flute spacing. α is the so called take-up factor defined as the ratio of the length of the unfluted corrugated medium paper to the length of the fluted geometry, and it is specific for each fluting medium profile (see table 1) and corrugating set of rolls used in the plant. **k** and **b** are constants.

Table 1. Fluting medium profile types (Twede & Selke, 2005:408-409)

Flute profile type	Approximate flute height [mm]	Approximate take-up factor - α
F Flute A very fine flute, (also known as microflute), giving excellent flat crush resistance and rigidity	0.74	1.25
E Flute A fine flute with excellent flat crush resistance	0.99 – 1.80	1.29
C Flute A larger flute than 'B', offering greater compression strength, but it may be crushed more easily	3.48 – 3.68	1.38 – 1.43
B Flute By far the most widely specified flute profile, due to its superb robustness (difficult to crush), good compression strength and compactness	2.21 – 3.00	1.32
A Flute The largest flute, but seldom used at present	3.99 – 4.90	1.54

This miniature buckling hypothesis and the associated model take into consideration the opposite effect the increase in paper density has on paper compression strength and bending stiffness, i.e. compression strength increases with density caused by increased wet pressing, but bending stiffness decreases at the same time from decreased paper thickness (Popil *et al.*, 2004). The resulting model shows that for lightweight liners, there is a limit where density increases will lead to buckling, limiting the ECT of the corrugated board, as shown in figure 3.

Koning (1975) developed a theoretical model, relating the improvement in container's compressive strength to increasing the modulus of elasticity (cross direction) of the used linerboard. Using this model, Koning (1978) indicated that a theoretical relationship exists between the compressive stress-strain characteristics of the corrugated board's components and the compressive strength of corrugated fiberboard containers.

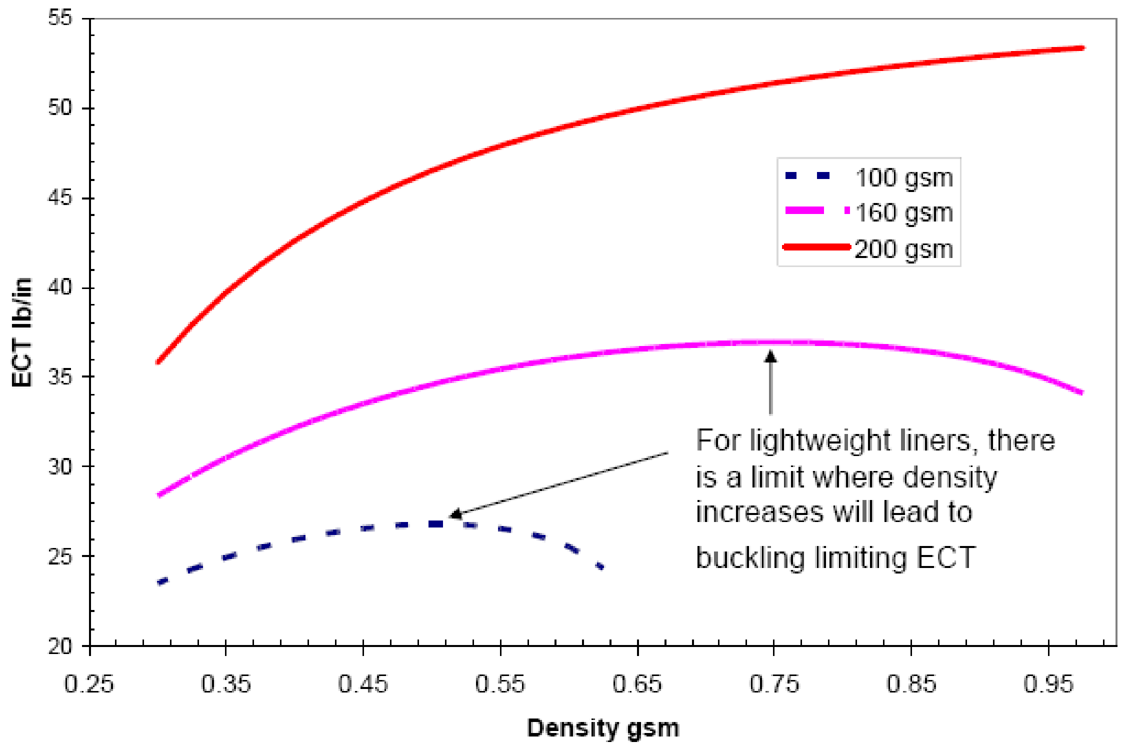


Figure 3. Predicted ECT versus liner density (Popil *et al.*, 2004)

A model by Johnson, Urbanik and Denniston (1979) treats the combined board component elements as a case of inelastic buckling and assumes the components are isotropic rather than orthotropic. The solutions are nonlinear and require empirically fitted CD compressive stress-strain curves. This approach requires specialized testing and a sophisticated computer analysis, as demonstrated by Gunderson (1983 & 1984).

Later Johnson and Urbanik (1989) considered the CD edgewise crush analysis and the elastic stability of a subsection of corrugated fiberboard characterized by a repeating sequence of microplates joined along the linerboard-medium attachment points. In their buckling theory linerboard elements between the corrugations of corrugated fiberboard can be viewed as short wide columns. Column ends are elastically restrained by the corrugated medium. The applied buckling theory demonstrated the importance of both MD and CD stress-strain properties to edgewise compression strength of corrugated board.

The relationships between paper and board properties have become progressively more complex as the models have been refined to take into account all of the important structural and component characteristics. The model by Johnson *et al.* (1979) is a good example, as commented by Van Eperen and Sprague (1983). Van Eperen and Sprague (1983) indicated that such relationships are of great value for research and development purposes, and may ultimately find a role in everyday business. However, such models are too complicated for practical use.

The second and simplest approach reported by Whitsitt (1988) is to sum the compressive strengths of the components (linerboards and medium) allowing for the draw of the medium profile type (see table 1). This approach gives good predictive accuracies if based on appropriate statistical weighting factors, and therefore it would be used for the current study. The author further indicated that the edgewise compressive strength of the board is also dependent on the quality of corrugating converting.

The general format of the mathematical model to estimate the ECT of the board from the compression strength of the liners and fluting medium is given by the so called **Maltenfort equation** (6) (Markstrom, 1999):

$$\mathbf{ECT = k\,(\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F})} \qquad \mathbf{(6)}$$

Where $\boldsymbol{\sigma_c}$ is the compression strength of liners and fluting medium paper used for the construction of the board. The paper industry employs different standardized methods, which will be discussed later, to measure the compression strength of paper, such as short-span compression test (SCT), ring crush test (RCT), crush/Concora liner test (CLT) and corrugated crush test (CCT). α is again the so called take-up factor of the specific fluting profile used (see table 1).

Theoretically the constant **k** should always be equal to unity, regardless of the paper compression strength test used, but due to testing errors, limitations in the test methods, as well as manufacturing variables at the corrugating plants, the challenge is to find a more representative value, which would assist in predicting more accurately the board and consequent box performance. Also the above statement for **k** being equal to unity would be only valid if the strain to failure is equal for both liner and fluting medium, and this is seldom the case (Markstrom, 1999).

Whitsitt and Sprague (1986) investigated and presented the factors affecting the retention of compressive strength during fluting, i.e. the impact of the fluting process on the constant – **k**. Their results indicate that 15-20% of the ECT potential of corrugated board is lost during the fluting process. This occurs because the fluting process causes large reductions in the edgewise compressive strength of the medium, under both hot and cold forming conditions. The reductions in strength are caused by the high bending and tension stresses induced in the medium paper during fluting. During the process the medium is exposed to high stresses. If these stresses are too high, visible fractures of the medium will occur and the board will be useless. At lower stress levels visible fracturing will cease, but their research showed that there is still heavy damage to the medium, resulting in a serious loss of end-use performance.

The paperboards are also subjected to steaming during manufacture, which relieves built-in stresses in the sheet (Seth, 1985). This can reduce the elastic modulus and compressive strength of the sheet by 5-15%. Since the paper components are sampled before they have been subjected to any treatment, it should not be surprising to find that their combined strength is higher than that of the corrugated board made from them. The extent of the damage to paperboard resulting from manufacturing conditions is difficult to determine, but Seth (1985) indicated that it would be different for different plants, and within a plant, different for different flute types.

Seth (1985), when developing similar ECT correlation models, indicated that it can be expected the ECT of the corrugated board measured by the column-crush test would be lower than the sum of the strengths of the components measured by short-span compression test method (SCT), used in his investigation, because the initiation of failure is not only governed by the presence of defects, but also by the component that has the minimum resistance to failure.

A further influence on **k** is that the measurement of combined-board ECT is prone to error in specimen preparation and testing procedures and this could result in lower strength values (Koning, 1983: 385-408 and Ericksson, 1979a&b). The strength of the board and papers are also measured at different strain rates, as noted by Seth (1985). The author indicated that a precise comparison is difficult, but it is reasonable to assume that the rate for paper compression in SCT method is an order of magnitude higher. The combined board strength, measured at a comparably higher rate, could probably be 10% higher (Moody & Koning, 1966).

The sizes of the samples used for the measurements of ECT of combined boards and SCT for paper components also could affect the results (Seth, 1985). While edgewise compression strength of combined board is measured on specimens of finite length (ECT methods to be further discussed in Paragraph 2.2.2.), the strength of the board's components is measured on test spans that are only 0.7 mm long (when using the SCT method to be discussed later). In a comparison of the short and finite-span methods for measuring the SCT of paper, Seth (1983) showed that the short-span method gives results that are generally between 15-30% higher than the finite-span method. This discrepancy can be explained by the different boundary conditions for stresses in the two samples and by the higher chance of initiation of failure by defects in the longer sample, as discussed by the author.

Ericksson (1979a&b) pointed out that 20-30% higher ECT values are obtained if instead of waxing (to be discussed later), the edges of the combined board test pieces are reinforced by attaching four pieces of linerboards onto the facings of the sample with pressure sensitive tape, leaving 2-3 mm of free span in the middle. These higher ECT values correspond well to the sum of the intrinsic strengths of the components.

Further, the equation (6) format shows linear relationship between the corrugated board and its components' intrinsic compression strength with y-intercept equal to 0. However, the extensive literature review revealed that different experimental determinations of these relationships show different y-intercept (**a**) values depending on the testing methods used:

$$ECT = \mathbf{k}\,(\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F}) + \mathbf{a} \qquad \textbf{(7)}$$

Y-intercept cannot be explained physically, i.e. if no compression is provided by the paper components, the board should have no compression strength. However, most authors of such models used the experimentally obtained data and forced the linear fits to intercept the y-axis at 0, still retaining statistically significant mathematical fits and high degree of correlation.

Also sometimes data analysis shows that the ratio of edgewise compression strength of board to board components' compression strength is curved so much so that a single straight line formula does not fit the data in a satisfactory fashion. An appropriate nonlinear relationship would describe the data better than a straight line. To preserve simplicity, authors such as Van Eperen and Sprague (1983) have chosen to divide the grade range into two parts, and fit each with a straight line formula, depending on the paper components' basis weight (thickness/density). However, Popil *et al.* (2004) indicated that this is the direct result of low bending stiffness and an increased tendency of interflute buckling prevalent with lightweight linerboards. The authors further comment that since Van Eperen and Sprague (1983) completed their work, high ring crush linerboards have become common. The increase in vertical compression strength per unit weight has been achieved primarily through wet pressing. This has resulted in increased densification, but lower bending stiffness as also commented above. The outcome resulting in a greater proclivity of interflute buckling with the current lightweight linerboards.

The models found in literature are summarized and shown in Appendix 1. It can be seen that compression strength of corrugated board and its components can be measured by different techniques, and simple models could be then fitted to correlate these properties. Caution should be always exercised when using this approach, because of the influence of the board manufacturing process. However, predicted ECT values from the component properties should be a good indication of the strength potential of the board in compression (Steadman, 2002: 622-623).

2.2. Paper and board compression test methods

2.2.1. Edgewise compression strength testing of paper

As already indicated above, in order to develop a representative mathematical model correlating the compression strengths of board and its components, an adequate paper testing method should be utilized. Any deficiencies and errors, resulting from the testing methods used to generate the data for the models, are integrated in the dimensionless constant – **k**, evident in all existing models, as already discussed in paragraph 2.1.2.2.

In general two principally different uses for edgewise compression test of single paper sheets can be identified (Fellers & Donner, 2002: 481-521). The first use is for quality control in paper mills and quality acceptance in corrugating and box plants. For such applications the test method must be precise and correlate to the performance of the boards, i.e. **k** should approach unity, as well as it has to be simple, rapid and reproducible over time. The second use is as a research and development tool, where the method would be used to design and optimize products' performance. As indicated by the authors, the method for the second use should be based on fundamental principles of mechanics.

The currently available paper compression test methods produce results that can differ 30% or more for the same material (Fellers & Donner, 2002: 481-521). Therefore it has been considered necessary to discuss this here in more details, as the influence the paper testing method would have on the mathematical correlation and on the constant **k** in particular, would be largely dependent on the paper testing method selection.

According to Fellers and Donner (2002: 481-521), the main challenge for all compression strength tests of paper is to introduce a compressive force into the plane of the sheet in a way that causes a pure in-plane compression deformation and failure. Often out-of-plane bending and buckling is evident. This problem is overcome to some extent by either using a short span, by supporting the specimen against out-of-plane deformations or by selecting proper specimen geometry. The principle of load application and specimen geometry for the different test methods are shown in Appendix 2.

2.2.1.1. Short-span specimen geometry

The basic principle behind the short-span specimen geometry is to use such a short span, that crushing of the specimen occurs before any buckling of the paper strip takes place. The Concora liner test (CLT) (Maltenfort, 1956) and STFI SCT (Fellers & Jonsson, 1975) are examples of methods currently used in accordance with this principle.

2.2.1.2. Plate-supported specimen

The short-span compression test is able to simply provide a measure of the material compression strength, but the influence of the clamps prevents the measurement of stiffness properties. Stress-strain characteristics in compression, however, can be evaluated with the sheet restrained on each side by solid metal plates. The main problem with this commercially unavailable test is the development of small-amplitude waves, when a single sheet (especially thin paper) is laterally supported. This can be minimized by applying lateral support when closing down the clearance between the solid metal plates. Friction is then a concern and often lubricants are used. Three different methods based on this principle have been developed for determination of stress-strain curve of papers in compression – STFI Solid support test (Fellers *et al.*, 1980), PPRIC Plate support test (Seth & Soszynski, 1979) and FPL Lateral support test (Jackson, Koning & Gatz, 1978).

2.2.1.3. Blade-supported specimen

By providing lateral support using slender blades with very short distance in between, buckling prevention of the sample can also be achieved. Stress-strain curves in compression can also be obtained. However, certain problems such as blades misalignment, rough paper surface, as well as difficulties in use were reported as major shortcomings. The following tests using this approach were reported - STFI Blade Support Test (Cavlin & Fellers, 1945), Weyerhauser Lateral Support Test (Stockmann, 1976) and FPL Vacuum Restraint (Gunderson, 1983).

2.2.1.4. Cylindrical geometry

The cylindrical geometry allows for stability of the specimen when loading in the plane of the sheet. However, one concern with this principle is the support of the loaded edges, which can fail. The other problem is associated with the creation of seam when forming the rolled geometry. Some methods using this approach utilize adhesive to overcome the presence of the seam. The following test methods using cylindrical geometry are known – Ring Crush Test, IPC-Modified Ring Crush Test (The Institute of Paper Chemistry, 1963b) and FPL Supported Cylinder Test (Setterholm & Gertjejansen, 1965).

2.2.1.5. Corrugated specimen

The principle of these methods is to simulate the corrugated shape of the fluting medium in corrugated board. It is therefore used to evaluate the contribution of the medium to the compression strength of the combined board. Edge crushing is also problematic. Different methods utilizing this principle exist – Concora Fluted Crush Test (Maltenfort, 1956), H&D Stiffness Test (Ostrowski, 1960) and Corrugated Crush Test (Langaard, 1968).

2.2.1.6. Comparison of different methods

A study was undertaken at the Institute of Paper Chemistry by Kloth, Whitsitt and Fox in 1977, to comparatively evaluate six methods of measuring the CD edgewise compression strength of linerboard and corrugating medium. The methods were compared in terms of maximum load, test variability, correlation to combined board edgewise compression strength, correlation to each other, and relative ease of testing. The compression test methods studied were Regular ring crush test, Modified ring crush test, Liner edge crush test (LECT) - similar to Concora liner test, Concora fluted crush (CFC) - medium only, FPL lateral support compression test and Weyerhaeuser lateral support compression test. The RCT and LECT/CFC tests have advantages for quality control purposes considering they are the easiest tests to use and relate well to the ECT-strength of combined board. Until the question of frictional interference between the specimen and the sides of the FPL fixture can be resolved, it appears that the Weyerhaeuser lateral support test is the one most suitable for research purposes.

More recently Fellers and Donner (2002: 481-521) indicated that the results of various compressive strength measurements differ in most cases because of sample out-of-plane deformation, friction, deformation rate, moisture, temperature, loading uniformity, sample preparation, artificial constraints, clamping effects, etc. Figure 4 illustrates this by plotting CD compressive strength values of linerboard against basis weight according to different methods. The authors further emphasized the two major themes which account for discrepancies in the results, being due to large-scale structural instability of the sample, as well as the weak-link effect, arising from differences in sample size among different tests.

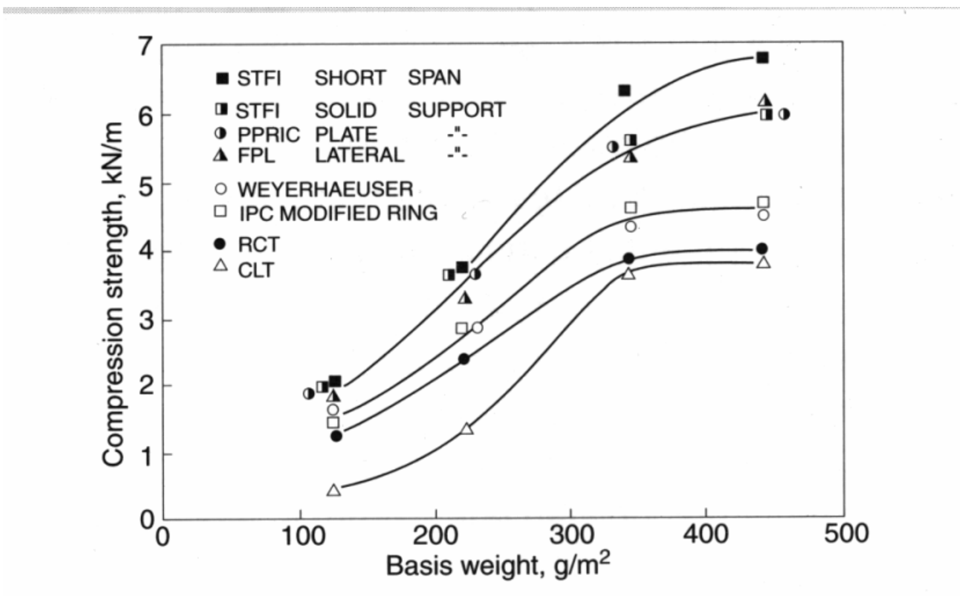


Figure 4. Compressive strength of linerboard in CD vs. basis weight using different testing methods (Fellers, 1983)

From the long list of testing methods in this paragraph, only the following methods are currently commercially available and used in facilities related to the paper and board manufacturing industry – Concora liner test (CLT), STFI SCT, Ring crush test (RCT), Corrugated crush test (CCT), H&D stiffness test and Concora fluted crush test (CFC). The rest of the tests are only utilized for research and development at different organizations related to the industry.

2.2.1.7. RCT vs. SCT

The two most widely used paper compression strength test methods in the industry are the Ring Crush Test and the STFI Short-Span Compression Test. Batelka (2000) reported that currently, about half of U.S. paperboard manufacturers use the

RCT method and about half use the STFI SCT method. The RCT is also commonly used test in the Australian paperboard industry (Jackson & Parker, 1998). The authors commented that the RCT is a more relevant indicator of box stacking performance than SCT. In the same time, Fellers and Donner (2002: 481-521) identified a number of deficiencies associated with the RCT method. However, despite these problems with the RCT method, it is still used widely for control purposes. Therefore for the purpose of this study, it was decided to further investigate these limitations.

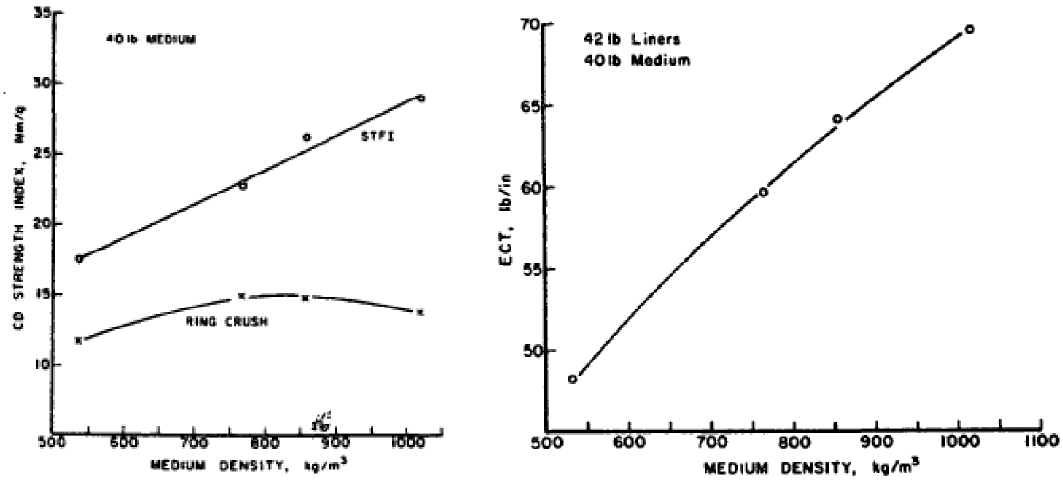
The analysis conducted by many authors, including Seth (1984), Dahl (1985), Rennie (1995), Batelka (2000), Ju, Gurnagul and Shallhorn (2005), Frank (2003 & 2007) demonstrate that:

- the RCT and the STFI SCT are not interchangeable test methods;
- the failure mode is not the same for the two tests;
- the tests are measuring different compressive strength properties of the paperboard affected by different paper mill process changes;
- a universal formula to convert SCT to RCT has failed because there is no simple relationship between the two values as they are dependent on furnish and the type of forming equipment used;

Also according to Whitsitt (1985):

- the STFI SCT is coming into wider use;
- the SCT is simpler, more accurate and appears to have many advantages;
- ring crush is a more complex test than the short span type test because of its cylindrical geometry;
- there are also differences in mode of failure, as commented by the other authors;

In ring crush tests on lightweight materials failure occurs by buckling. On heavy weight materials failure occurs at the loaded edges, which are weakened by cutting as the specimens are prepared. Whitsitt (1985) further claimed that because of the differences between the tests, no single relationship will hold between them under all papermaking conditions. For example, when fluting medium is wet pressed to varying degrees, the reported results in figure 5a show that CD ring crush exhibits a maximum at intermediate densities of around 750-850kg/m³, whereas the STFI SCT results increase steadily over the density range. The ECT results achieved with these mediums increased in the same way as the STFI SCT results, as shown in figure 5b. Thus the STFI SCT results were more indicative of the fluting medium contribution to ECT, than the RCT results.



(a) **(b)**

Figure 5. (Whitsitt, 1985)

(a)SCT_{CD} and RCT_{CD} show different trends with increasing density for 195gsm fluting

(b) Wet pressing increases the ECT of combined board

Batelka (2000) further commented that the relative technical merits of the two test methods have, to date, been based on speculation. He suggested that what is needed by the industry is a well designed, objective, thorough, and scientifically correct investigation to define conclusively whether the RCT or the STFI SCT is the technically correct test method to use to predict accurately and precisely the end use compression strength performance of paperboard materials (ECT and BCT).

Seth (1984) pointed out that the RCT method does not measure the true intrinsic edgewise compressive strength (IECS), important for ECT development. In view of his results and the increased importance of compressive strength of linerboard and medium in container design, he recommended that tests, such as the RCT should not be used. The author indicated that the RCT results depend on both the compressive strength of the sheet and stiffness of the specimen structure. He recommended the use of compression test that measures the true potential of the sheet under edgewise compression, such as the STFI SCT.

In opposition to this, Frank (2007) showed that RCT and SCT tests can be both used to evaluate the compression strength of corrugated board components, and can be correlated with combined board strength (ECT). The author demonstrated that because each test evaluates paper strength at a different length scale, the correlations are not of equal quality. Earlier, Frank (2003) showed that once the effect of paper basis weight is excluded, the correlation between SCT and RCT results is largely lost in the noise. This noise, or measurement variability, significantly influences which test can better predict combined board performance. Frank (2003 & 2007) found that even though SCT measures a more fundamental paper property, the RCT correlates somewhat better with ECT strength, even when smaller number of testing paper specimens is used to measure the paper compression strength. This was again related to the difference in failure mechanism within each paper test in relationship to the failure length scales in combined board, as well as to the level of noise. Therefore the RCT appears to serve as a better predictor of final board performance.

Rennie (1995) showed that RCT and SCT results can be correlated well, if the bending stiffness (**T**) and thickness of the paper (**t**) is included in an empirical model:

$$\mathbf{SCT = RCT + 0.005T/t^2} \qquad \mathbf{(8)}$$

Dahl (1985) indicated that normalization of strength test results to unit mass of sample is a good method for data presentation. The author aimed to define paper compression property parameter independent of basis weight over a reasonable range. The compressive strength results of his study, indexed to grammage, are plotted against grammage in figure 6, to serve as an aid in determining which weights of paper might be unsuitable for RCT testing. For indexed results in the legitimate test range, the data points should form a flat horizontal curve for that domain. The obtained results point out that over the full range the STFI SCT index curves are essentially flat and the ring crush curves are not. For the low density hand sheets, the ring crush index (RCI) curve shows a level region for grammages greater than 150 g/m^2. Below 150 g/m^2, the RCI values decrease and suggest that ring crush is not a valid test for that region. For the high density hand sheets, the plateau region extends down only to about 225 g/m^2. Below that weight, the RCI curve declines sharply with decreasing grammage, suggesting that ring crush testing of a high density 205-g/m^2 linerboard is not correct. The author recommended that TAPPI method T818 for RCT should be revised, and the valid grammage range be defined.

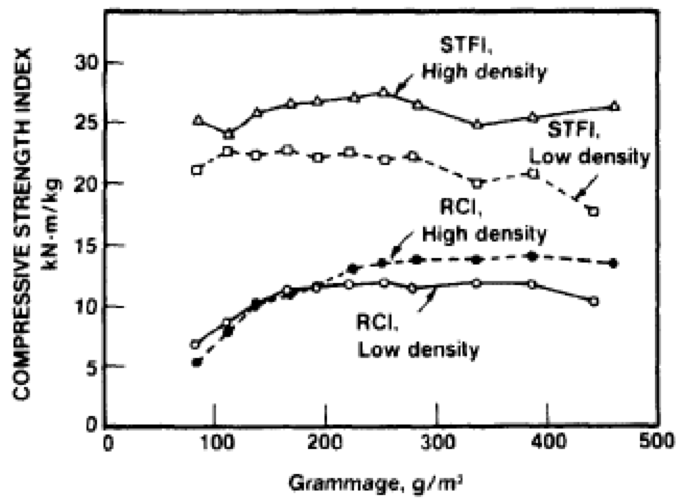


Figure 6. Compressive strength index vs. grammage of hand sheets. The transition points from flatness occur at different grammages for the high and low density samples (Dahl, 1985).

Shallhorn, Ju and Gurnagul (2005) modeled the failure of the paperboard in RCT and showed that the failure of the ring crush specimen at low caliper can be described as global buckling. At higher caliper, the mode of failure is described as localized at the loaded top edge and is initiated by the development of a bending moment at the unsupported loaded edge. In this case the failure is related to the short span compression strength of the sample. The authors concluded that for thicker papers paper making processes that affect the SCT result will influence RCT to much the same extent.

Based on the above literature findings, it can be seen that somewhat poorer correlation should be expected between the ECT results of corrugated boards and RCT results of the paper components, due to limitations in the RCT method and the failure mechanism. SCT results of the paper components should correlate better to the ECS of the corrugated board.

2.2.2. Edgewise compression strength testing of corrugated board

The edgewise compressive strength (ECS), (also called edgewise crush resistance or ECT-strength), of corrugated board was defined by Markstrom (1999) as the maximum compression force that a test piece will sustain without any failure occurring. There are a number of different test methods for ECT measurement (see Appendix 3). The various test methods are fundamentally similar – a test specimen of corrugated board is placed between the platens of a compression or crush tester with the flutes oriented vertically. The specimen is subject to an increasing compressive force until it fails (Steadman, 2002: 622-623). The maximum force at failure expressed per unit length of the specimen is recorded as the ECT result of the board. However, Markstrom (1999) emphasized that differences of up to 30% can be seen between the results obtained by the different methods. This is very unsatisfactory, because it is expected the results from the different methods to lead to similar values of board compression strength. On the positive side, the author noted that at least the different methods rank the different boards in the same order. Also to have a good and acceptable edgewise compression strength testing method, the following must be in place:

- Measures what is intended to measure, i.e. pure compression strength of the whole corrugated test piece;
- Is accurate and reproducible;
- Is easy to perform as a routine method in a corrugated board laboratory;

A study conducted by the Institute of Paper Chemistry (1965) reported that the mechanical properties of fiberboard are also sensitive to rate of application of stress or strain, requiring consideration of test rates for formulating test procedures. It was shown that a definite trend of an increase in edgewise compression strength with increase in test rate is evident, as may be anticipated for viscoelastic materials.

The different methods available differ mainly by sample geometry and dimensions, the cutting equipment used for board preparation, the rate of loading, and the use of edge reinforcement. According to Steadman (2002: 622-623), the test methods can be categorized into two main groups:

2.2.2.1. Methods avoiding edge failure of the specimen

This group includes the Edge reinforcement method, known as TAPPI T811, the Neck-Down method (TAPPI T838), the Edge clamping method (TAPPI T839), the Japanese industrial standard (JIS Z-0401) and some others (see Appendix 3).

In the TAPPI T8II, which is the only test method approved for the alternative Rule 41/Item222 (Gutmann *et al.*, 1993), the specimen is cut to maintain suitable slenderness ratio, preventing sample buckling and ensuring the specimen failure under pure compression (see paragraph 2.2.1.1.). The loaded edges of the specimen are reinforced by dipping them in molten wax. However, this procedure of sample preparation is tedious and time-consuming, thus not meeting one of the criteria set above for good ECS test method.

The Neck-Down specimen method introduced by Koning (1964) has been used very successfully in a number of research projects at the Forest Products Laboratory (FPL). The test however, has not yet spread widely, due to the fact that equipment for test-piece preparation has not been commercially available until recently. The method is considered to meet all three criteria for suitable ECS method, since the development of an extremely simple and rational method which produces circular neck-down test pieces with great accuracy.

TAPPI T839 eliminates the use of edge waxing by using a clamp to reinforce the edges. It effectively clamps the upper and the lower 20mm of the specimen, leaving an unsupported span of approximately 10mm in the center. However, it has been shown that the clamping force is extremely critical and that it must be adapted for different flute grades. It is also in exceptional circumstances that the edge compression failure can be avoided by this method (Markstrom, 1999). This method does not meet with certainty any of the three criteria for a good testing method.

The JIS Z-0401 method builds upon the same principle as the above mentioned clamping method. This method also is distinguished by the fact that the specimen has been cut with a sharp waist. Cutting of the samples is complicated and the method does not necessarily measure what is intended to measure – pure ECS (Markstrom, 1999).

Other alternatives have also been proposed with small modifications to the above methods, but have not gained much popularity due to not meeting the suitability for testing methodology. Some of these methods include – the Morris Clamping method - TAPPI T841 (Maltenfort, 1988), Reinforced Liners method (Eriksson, 1979a&b) and Long Span method (Westerlind & Carlsson, 1992).

2.2.2.2. Methods using rectangular specimen to minimize edge damage

This group includes the SCAN (P33:71), FEFCO (No. 8) and ISO (3037:1994) standard methods, which specify different specimen sizes with no edge reinforcement (see Appendix 3). The specimen is supported between two blocks to keep it perpendicular to the platens of the compression tester during the initial loading (Steadman, 2002: 622-623).

The FEFCO (No. 8) method has spread widely in Europe, although this method does not try to avoid edge failure. It is now known that generally the test result depends to a great extent on whether or not the edge surfaces of the test piece are parallel (Markstrom, 1999).

2.2.2.3. Comparison of different test methods

A study, initiated by Schrampfer, Whitsitt and Baum in 1987, was directed toward improving ECT measurement technology by developing a safer, simpler, and more efficient method of sample preparation and testing. Three alternate ECT procedures involving several types of sample cutters and holders were compared to the standard TAPPI T811 method. The Japanese ECT test fixture was used in combination with a 2-inch Billerud cutter, and it was found to compare the most favorably with the TAPPI method. Results obtained with the original hand tightened version of the fixture showed excellent agreement with TAPPI results, and exhibited lower variability. Later work with a spring-operated version of the fixture showed ECT results to be sensitive to clamping pressure. Double wall board and high series single-wall board required a higher clamping pressure to achieve good comparison with TAPPI results. An easy-to-use design involving the original fixture fitted with the appropriate springs has been recommended. The two other ECT procedures investigated included a SCAN-method/Billerud cutter combination and a Weyerhaeuser holder/Weyerhaeuser cutter combination. ECT results were considerably lower than TAPPI values using these methods. Sample height was also investigated and found to have no effect on ECT in the range of 1.5-2.0inches. Several types of rigid-platen compression testing machines were compared to the flexible-platen H&D compression testing machine, and no significant difference in ECT results was detected.

Markstrom (1999) also reported the comparative ECT results obtained by using the FPL Neck-Down method, the TAPPI T811 waxed edges method, the Japanese industrial standard (JIS Z-0401) and the FEFCO (No. 8) method. The results from this study carried out by FEFCO and presented in 1987 in Nice are shown in figure 7. Markstrom's (1999) commented that differences of up to 30% are well presented in this figure, together with the fact that the different methods rank the different boards in the same order.

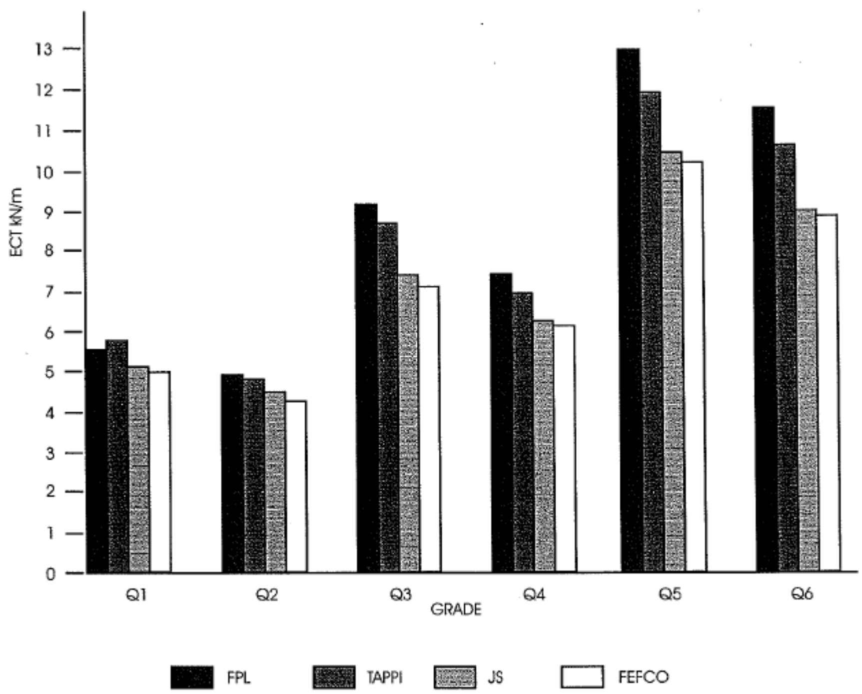


Figure 7. Comparison between different ECT test methods (Markstrom, 1999)

In a study discussed by Markstrom (1999) it was found that the Neck-Down method gives the same test results as the TAPPI T811 up to about 15kN/m. Above this value, the waxing of the edges no longer prevents failure and the method gives lower results. Comparison between FEFCO and the FPL Neck-Down method are also shown and a mean difference of about 31% is reported.

Following these investigations the FPL Neck-Down method was recommended by Markstrom (1999) to resemble best the failure of the corrugated board under pure compression. Therefore when this method is used to model the correlation between the board components' compression strength and the ECT of the board, the dimensionless constant **k** in equation (6), should approach unity and can be ignored completely, on the condition that the other factors affecting it, are minimal. An example of this is the results reported by Koning (1964). The author showed the correlation between RCT of the board components and the ECT of the corrugated board, measured using the Neck-Down FPL method, where the obtained dimensionless constant (**k**) was equal to ***1.302***. Therefore **k** is always determined experimentally.

2.3. Paper and board performance at high humidity

One of the major factors affecting the stacking performance of corrugated containers is the moisture content of the board. The equilibrium moisture content is dependent on the ambient temperature and relative humidity (RH) among other factors. It is well known that a corrugated box loses 50-60% or more of its short-term top load box compression strength when the RH is increased from 50 to 90% (Whitsitt & McKee, 1972). Moisture and temperature are perhaps the most important environmental variables affecting the strength properties of paper. Paper will generally exhibit both elastic and plastic behavior, the relative amounts depending on composition and environmental conditions. An increase in moisture content generally results in a reduction in ultimate paper strength properties. This is usually attributed to a reduction in inter-fiber bonding rather than fiber tensile strength. Swelling effects may also increase stress concentration within the network (Waterhouse, 1984). Therefore it has been considered rather important to investigate how paper and corrugated board properties are affected by change in the surrounding environmental conditions.

2.3.1. Moisture content and the effect from changing environmental conditions

The moisture in the paper changes in relation to the surrounding conditions (Alava & Niskanen, 2006). At certain humidity conditions the paper will reach equilibrium moisture content. So the moisture in the paper would be dependent on the equilibrium conditions and not on the production specification for moisture content. At high humidity, the % moisture would tend to be higher and vice versa. Therefore Waterhouse (1984) recommended that it would be more meaningful to compare properties at a given moisture content and temperature rather than at a fixed RH and temperature.

The moisture content of paper at a certain relative humidity is different in adsorption when coming from dry conditions and in desorption when coming from humid conditions (Kajanto & Niskanen, 1998: 223-257). Depending upon the humidity history, the moisture content can be anywhere between the boundary curves as shown in figure 8a&b (Prahl, 1968). This phenomenon is known as the *hysteresis effect* and its various mechanisms have been explained by Everett (1967: 1055-1110), Yamazaki and Munakata (1993: 913-934), Urquhart and Williams (1924), and Barkas (1951).

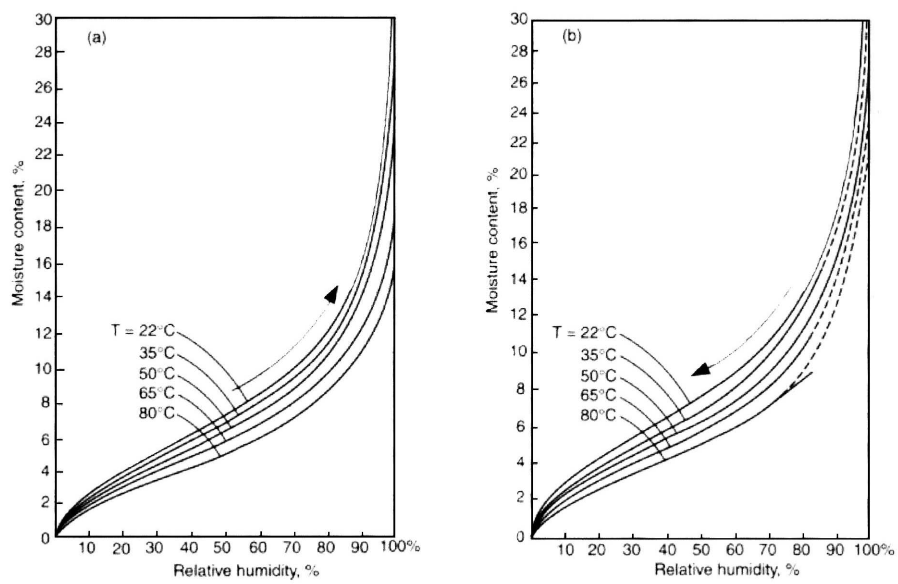


Figure 8. Moisture content of paper at different temperature when the relative humidity of ambient air is varied (Prahl, 1968).

2.3.2. Paper moisture content and the effect on paper properties

Moisture and temperature are perhaps the most important environmental variables affecting the strength properties of paper, as already indicated. Prior history of moisture gain and loss also affects paper properties. Since paper is a viscoelastic material, it does not return to the same dimensions after drying and rewetting, or after humidity cycling. There is a progressive change in dimensions after each humidity cycle, with the greatest change occurring after the initial cycle as seen in figure 9.

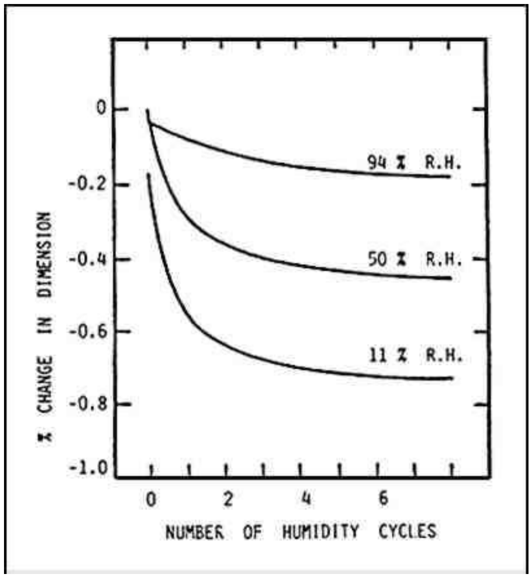


Figure 9. Effect of repeated humidity cycling on the dimension of paper in MD (Wink, 1961).

Wink (1961) studied dimensional changes in linen writing paper during changing relative humidity conditions. He exposed samples to the humidity cycle of 50→11→50→94→11%RH in increments of about 15% RH. He repeated the cycle eight times, with the temperature at 23°C. The author found appreciable shrinkage at the three relative humidity levels. The curves show that the stress-relaxation effect dominates the swelling effect to such a degree that all dimensions at 94% relative humidity were smaller than the initial dimensions at 50%RH.

Irreversible impact on physical properties, resulting from an excursion of paper to a high RH, is often observed. This evidently originates with the swelling and shrinking of the fibers and with the relaxation of dried-in or built-in stresses. The major effect occurs on the first exposure of paper to a high RH, exceeding approximately 65%. It is dependent upon the extent of the excursion and it could permanently alter dimensional and strength properties. These changes are non-recoverable by manipulation of the moisture content or by preconditioning and conditioning the paper, concluded Wink (1961).

Moisture is so critical to the properties of paper that the ISO and TAPPI standards for temperature and moisture paper conditioning prior to testing, requires a temperature of 23°±1°C and a relative humidity of 50%±2% (ISO 187, TAPPI Standard T402). The TAPPI standard acknowledges the discrepancy caused by the hysteresis effect in moisture content and recommends preconditioning the sample from below 50%, by adsorption. This same standard emphasizes the effect of preconditioning and the hysteresis effect in the section, "Importance of Preconditioning" - *The physical properties of a sample at 50% R.H. depend on whether the sample was brought to 50% from a higher or lower RH. This humidity hysteresis effect is a 5–25% of the test value for many physical properties. Conditioning down to 50% gives most papers a moisture content very nearly the same as conditioning up to 60%.*

In the same time, according to Crook and Bennett (1965), while the preconditioning procedure practically eliminates the hysteresis effect, it has little influence on the strain relaxation effects. The latter depends on the entire previous moisture history of the sample, especially on the conditions of initial drying and tension, and on the duration and degrees of subsequent excursions to high humidity (i.e. above about 58% RH).

2.3.2.1. Viscoelastic properties

As indicated above, based on the atmospheric conditions and historical exposure the moisture in the paper would differ leading to a different strength performance. To support this, theoretical models were established, correlating Elastic modulus and moisture content at different temperatures for H-bond-dominated solids (paper is the perfect example) (Batten & Nissan, 1987). The rate of change of Elastic modulus (**E**) with increasing moisture content (**w**) was reported by Zauscher, Caulfield and Nissan (1996) to follow the rule: **ln[E] = A - (C.I.)w**, where the negative slope of the curve **ln[E]** vs. **w** is constant over a wide range of moisture contents. **C.I.** is the Cooperative Index – a measure for the cooperative bond breaking effect of water. The cooperative index is a direct measure for the influence of water on elastic modulus.

Paper will generally exhibit both elastic and plastic behavior, the relative amounts depending on composition and environmental conditions. In cellulose, viscoelastic and plastic flow behavior will be influenced by the relative amounts of crystalline (ordered) and amorphous (less ordered) material present. A truly amorphous polymer has a well defined glass transition temperature $\mathbf{T_g}$, and at temperatures below $\mathbf{T_g}$ the polymer exhibits glass-like behavior, while above it, rubbery behavior. Glass transition or softening temperature ranges for some cell wall components and are shown in table 2. In the dry state at temperatures below $\mathbf{T_g}$ these components will behave as a glass. Moisture may be viewed as a plasticizer, which can effectively lower the $\mathbf{T_g}$ or softening temperature of these components. An increase in moisture content generally results in a reduction in ultimate strength properties. This is usually attributed to a reduction in inter-fiber bonding rather than fiber tensile strength. Swelling effects may also increase stress concentration within the network (Waterhouse, 1984).

Table 2. Softening temperatures of dry material (Waterhouse, 1984).

Cell wall Material	T_g (°C)
Cellulose	230
Hemicellulose	150-220
Lignin*	124-193

***Native lignin may be higher**

The stress-strain behaviour of paper changes with moisture content (Salmen & Back, 1977). At low moisture content, paper is stiff and brittle, and it fails at low strain values. At high moisture contents, the elastic modulus and stress levels are lower than at low moisture contents, and as shown in figure 10, breaking strain is higher. At the molecular level, the effect comes from the softening of the hemicellulose. Fibers and especially inter-fiber bonds gradually lose mechanical rigidity as moisture increases. In the end, fibers can be pulled intact from the wet paper. Salmen (1982) has studied experimentally and theoretically how moisture influences the elastic modulus of fibers and paper.

Back, Salmen, and Richardson (1983 & 1985) measured the transient mechanical behavior of paperboard during tension while sorbing moisture. They compared their results with researchers working on wool and other natural fibers. They concluded that the rate of moisture sorption governed the amount of transient behavior. As a result of transient behavior, stiffness and strength are a function of moisture content and the moisture content gradient. In other words, at equilibrium conditions for a given material, stiffness and strength are solely functions of moisture content. During moisture sorption, however, the rate of moisture change also affects stiffness and strength.

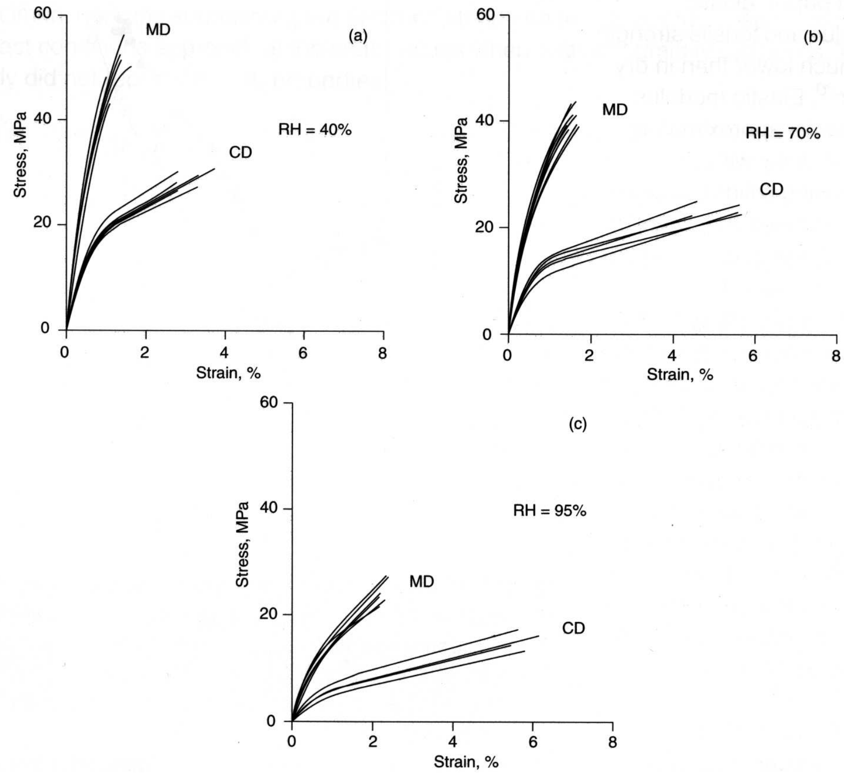


Figure 10. Stress-strain curves in MD and CD of paperboard at RH=40%, 70% and 95%. The corresponding moisture contents are 6.6%, 9.7% and 20% (Yeh, Considine & Suhling, 1991: 695)

2.3.2.2. Compression strength properties

In order to design corrugated boxes successfully for long-term storage, package designers must know the box strength required and the influence of environmental exposure on the performance of the container (Koning & Stern, 1977). Kellicutt (1960) found that corrugated fiberboard has the greatest compressive strength when it has low moisture content, and as the moisture content increases, there is a corresponding decrease in compression strength.

Van Eperen and Robbins (1994) conducted a study aimed at defining the relationship between moisture content and compressive strength of linerboard and corrugating medium, and determining whether the relationship is affected by the type or source of the paper. The performance of different basis weights standard, recycled, green liquor and high performance linerboards and fluting grades were evaluated at 20, 30, 40, 50, 60, 70, and 80%RH@23ºC. All samples were tested for moisture content, RCT_{CD}, and SCT_{CD}. The % moisture vs. %RH results from their study are shown in figure 11. The similarity in the results with figure 8 can be noted. The authors reported that there was no significant difference between the average moisture content of east and west coast (USA) paper samples. The results also showed that the average moisture content of linerboard samples was a little higher than that of medium samples, and this difference is statistically significant at the 0.05 probability level. The moisture content for recycled medium was clearly higher than that for other medium types.

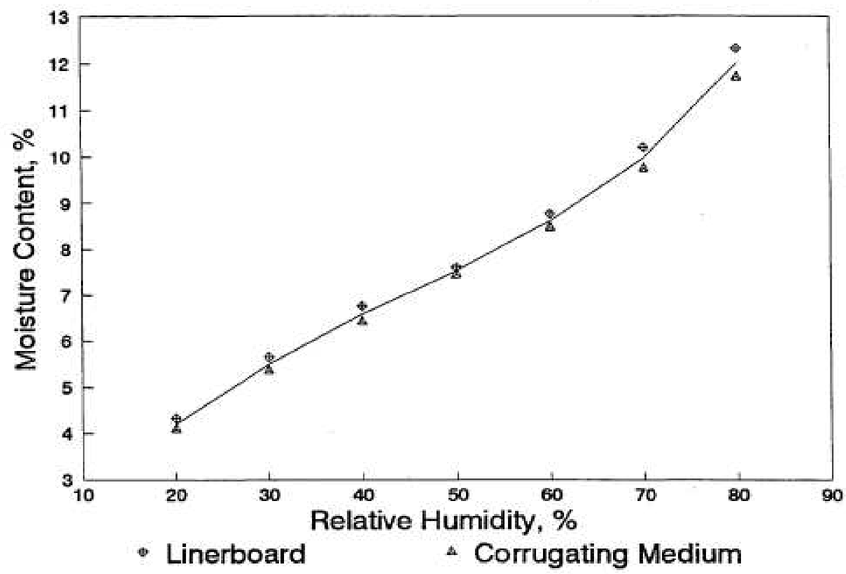


Figure 11. Average moisture content of linerboard and fluting grades at different relative humidity and constant temperature (23ºC) as reported by Van Eperen and Robbins (1994).

Van Eperen and Robbins (1994) found that over the range of 20 to 60%RH, similar linear relationships exist between RCT_{CD} and moisture content, and SCT_{CD} and moisture content (see figure 12a&b). Within this range RCT_{CD} decreases 5% for 1% moisture content increase, and SCT_{CD} decreases 7% for an increase of 1% moisture content. Above 60%RH, the rate of compression strength decrease gradually accelerates for both test methods. The authors could not find any significant evidence that the described above paper compression performance at different moisture content is significantly different for samples of different types or obtained from different sources.

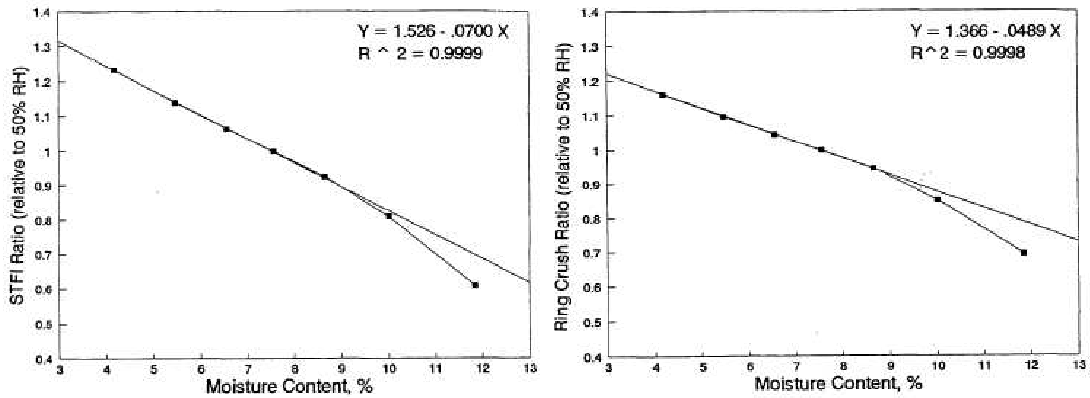


Figure 12. The effect of moisture content on STFI SCT and RCT for all grades as reported by Van Eperen and Robbins (1994).

Considine *et al.* (1994) reported that on average compression strength of corrugating medium in its cross direction is reduced by about 32% after changing from 50% to 90%RH at ambient temperature (around 26ºC). Similar results were obtained for 335gsm linerboard grades. The test method used in the experiment is not indicated to be a standard paper testing method, but rather some internal method, as cited by the authors.

Byrd (1984) reported that the reduction in compressive strength of linerboard and medium after exposure to 90%RH@73ºF is about 56%, when using the FPL Lateral support instrument (see paragraph 2.2.1.2. and Appendix 2). The corrugated board made of the same papers lost about 60% of its edgewise compression strength, when conditioned to the same atmosphere. The board was tested using the waxed edges TAPPI T811 method, as reported by Byrd and Koning (1978).

Whitsitt and McKee (1972) reported losses in edgewise compression strength of around 43% after exposure to 85%RH at 73°F. At 90% RH, 90°F the corresponding losses in edgewise compression strength amounted to about 55% on average. These changes were about the same in magnitude as were obtained in the case of the top load compression tests on the boxes in their study.

Boonyasarn *et al.* (1992) found that the moisture level in a box material is a very important factor which imparts box compression strength. The compression strength of all boxes tested by the authors was affected by the final moisture content of the box material after different cyclic humidity exposure. The relationship between loss of strength and material moisture content is shown in figure 13. The high correlation coefficient values depict a linear relationship, as concluded by the authors.

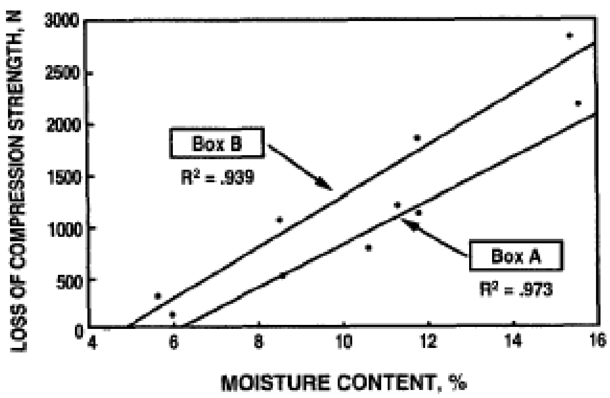


Figure 13. Relationship between loss of BCT strength and material moisture content. Initial BCT of Box A – 5,560N and Box B – 6,290N (Boonyasarn *et al.,* 1992).

Based on the above literature findings and in order to determine the mathematical models correlating paper and board compression properties at any environmental condition, it should be considered that before testing the boards' and their paper components' test specimens must be acclimatized at the same conditions for sufficient time.

2.3.3. Moisture-accelerated creep

An interesting observation about moisture effects is that creep rate becomes especially high if humidity varies (Considine *et al.*, 1989). In environmental cycles, creep rate is faster than it is at any constant humidity level of the cycle as shown by Gunderson and Tobey (1990: 213-226) in figure 14. This phenomenon is known as *accelerated creep*. Similar accelerated creep behaviour in tension, as well as in compression were also reported in a number of studies – Byrd (1972), Byrd and Koning (1978), Considine *et al.* (1994), Byrd (1984), Coffin and Habeger (1999), Haslach, (2000) and Chalmers (2001).

In a study conducted by Considine *et al.* (1994), it was suggested that the compressive strength of a material does not accurately predict the compressive creep performance for any environmental condition. The authors pointed that it is unreasonable to assume that the failure and deformation mechanisms are the same for compressive strength and creep tests. Unlike the compressive strength tests, creep tests allow the material to deform and distribute the stresses in an optimal manner. In creep testing, the visco-elastic nature of the material becomes important.

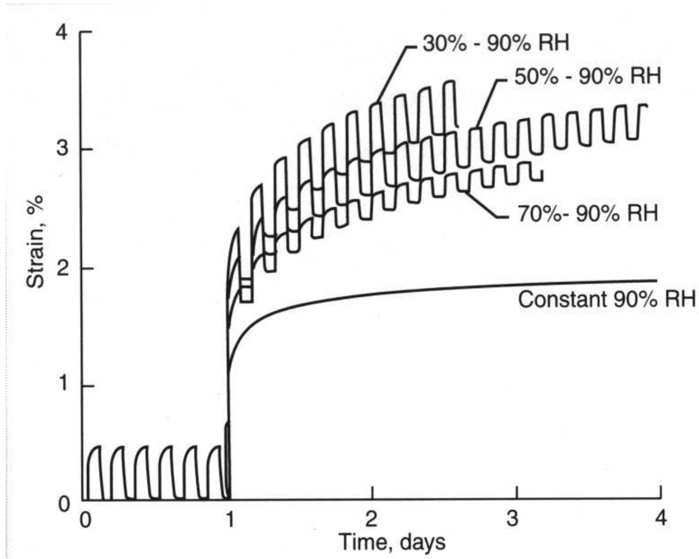


Figure 14. Compressive creep at constant and cyclic humidity conditions (Gunderson & Tobey, 1990: 213-226).

The compressive creep failure is important in containerboard grades, because containerboard corrugated board and boxboard boxes stacks often undergo storage for long periods. Creep rate increases with increasing humidity and temperature. Tropical conditions pose the highest requirements for the endurance of these box stacks. Daily variations in RH and temperature cause accelerated creep, which leads to creep failure much faster than in a constant climate. The *duration under load* becomes the important quality, and it is the time that a body can carry a fixed load before failure (Fellers & Laufenberg, 1995).

However, the scope of this study is limited to the evaluation of the short-term compression strength of corrugated board and its components after exposure to certain environmental conditions, thus moisture-accelerated creep behaviour of paper and its derivatives is only noted, but it will not be discussed any further.

3. Experimental

3.1. Apparatus

The following equipment, available at Sappi Technology Centre and shown in Appendix 4, was used for the experimental laboratory work:

- **TMI precision micrometer**, No. PTE 202, model No. 49-61, was used to determine the thickness (caliper) of paper samples conditioned at standard environment;
- **Mettler AE200 scientific scale**, No. 070B, model No. SNR K58687, was used to determine the paper samples weight after exposure to different environmental conditions;
- **W. Memment, Schwabach laboratory oven**, serial No. 454819, was used to obtain oven dried paper samples;
- **Hung Ta environmental humidity chamber**, type HT-58045A, No. 2361, was used to expose the precut paper and board samples to constant high humidity conditions at controlled temperature;
- **TMI short span compression tester**, No. P659, model No. 17-34-00-0002, PT/E193A, TC/BT002, was used to performed STFI Short span compression tests on the precut and preconditioned at different environments paper samples;
- **L&W crush tester,** No. PTE 180B, model No. 977093, was used to perform Ring crush and Edge crush tests on the precut and preconditioned at different environments paper and corrugated board samples, respectively;
- **L&W ECT sample cutter,** Type: 978877, No. 758, Code: 008, was used to cut the specified size board specimens for Edge crush testing;
- **RCT Messer Buchel Guillotine,** No. PTE 180A, was used to cut the specified size paper specimens for RCT (152.4 x 12.7mm), from each paper sample;
- **Messer Buchel and Ideal Guillotines,** PTE 302 and GL2, respectively, were used to cut the specified size paper specimens for SCT (70 x 15mm), from each paper sample;

3.2. Experimental design

As indicated in the scope of this investigation, variety of paper and corrugated board combinations were collected from three different corrugating board plants, which for the purpose of this report will be referred to as Corrugators 1, 2 and 3. In order to obtain close properties correlations and minimize the negative impact of machine and cross-machine direction paper properties variation, large sheets of linerboard and medium paper samples were collected directly from the top of each paper reel being loaded on the unwinding backstands of the corrugators. The corrugated board samples were then collected from the stacker at the end of the corrugating process. Depending on the board type being manufactured, two linerboard and one fluting or three linerboard and two fluting sample sheets were collected for the single wall and double wall corrugated board types, respectively. Figure 15 shows the different types of corrugated boards available. However, for this study only single and double wall corrugated board combinations were encountered.

Figure 15. Various types of corrugated board (Twede & Selke, 2005:407).

All paper and board samples were then clearly marked per combination and according to its position (L1, L2 or L3 for linerboards and F1 or F2 for fluting medium paper) for easy and accurate reference later. Cross-machine direction (CD) was also marked on all papers, to ensure correct CD compression strength evaluation (CD compression strength is in most cases critical for box stacking strength, as already clarified in paragraph 2.1.2.2.). The fluting profile types (B, C or E – only encountered) in each board combination were also recorded for medium paper take-up factor determination later.

The collected paper and corrugated board samples were then taken to the Sappi Technology Centre, where they were preconditioned for at least two days to 30%RH at 32ºC, followed by reconditioning to standard laboratory environmental conditions (50%RH at 23ºC) for at least another two days, all in accordance with ISO 187:1990(E) method.

All paper samples acclimatized at standard conditions were then used to cut sufficient number of specified size test specimens, as per standard testing methods listed in paragraph 3.3., to determine paper basis weight, thickness, as well as RCT and SCT in the appropriate cross-machine direction. The corrugated board samples were also used to cut the ECT test specimens. Board samples were also used to delaminate the fluting(s) from the linerboards in order to establish the accurate take-up factors for each fluting profile at each corrugating plant.

Basis weight and thickness were then determined for each paper sample. Randomly selected basis weight specimens were later used to determine equilibrium moisture content at high humidity conditions. Equilibrium moisture content was determined by weighing each of the different samples after exposure to the specified climatic conditions, followed by oven drying and weighing the same samples.

Two sets of paper and board testing specimens for SCT, RCT and ECT were prepared for each board combination. One set was used for compression strength properties determination after exposure to standard laboratory conditions of 50%RH at 23ºC. The second set was placed in the Hung Ta environmental humidity chamber for at least 24hrs exposure at high relative humidity (85%-90%RH at 23ºC). This was in agreement with the findings in literature that in order to determine the mathematical models correlating paper and board compression properties at any environmental condition, it should be considered that before testing the boards' and their paper components' test specimens must be acclimatized at the same conditions for sufficient time. It must be noted that the objective of this investigation was neither to determine the paper and board compression strengths correlation at certain conditions nor to establish the paper vs. board compression strength reduction between standard and specified high humidity conditions, but rather to establish mathematical correlations between corrugated board and its papers' compression properties. Thus the above experimental design allowed to use the same board and papers combinations, but using high humidity to decrease their strength properties. Based on the described in literature strength reduction behaviour, this experimental design would be similar to using weak paper and board combinations, doubling the data size to cover larger strength properties range and obtaining more accurate mathematical models. The mathematical models would allow for easy box stacking strength prediction at any environmental condition via board strength, by only testing the paper components at these conditions. It was therefore considered critical to place the different paper and board samples combinations in the humidity chamber at the same time to eliminate any difference in climatic conditions generated by incorrect operations or interruptions of the chamber.

After the exposure to the specified high humidity conditions in the environmental chamber, the specimens for each test were placed one set at a time in a plastic bag and rapidly tested to minimize moisture migration at standard laboratory conditions (50%RH at 23ºC).

3.3. Methods

The following International Standards were used in the experimental work of this investigation:

- **ISO 187:1990(E)** – Paper, board and pulps – Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples.

- **ISO 536:1995(E)** – Paper and board determination of grammage, where the test specimens for each paper sample had an area of 100x100mm.
- **ISO 534:1988(E)** – Paper and board determination of thickness and apparent bulk density or apparent sheet density.
- **ISO 9895:1989(E)** – Paper and board – Compressive strength – Short span test (SCT).
- **ISO 12192:2002(E)** – Paper and board – Compressive strength – Ring crush method (RCT).
- **ISO 3037:1994(E)** – Corrugated fiberboard determination of edgewise crush resistance (Unwaxed edge method). This International Standard is equivalent to the referred in this report FEFCO (No.8) ECT method.

4. Results and Discussions

4.1. Paper substrate and corrugated board physical properties

The results from the laboratory paper substrates and corrugated board tests are shown in table A5 in Appendix 5. The annotations 1 and 2 for ECT, SCT, RCT and Moisture stand for the test results obtained after exposure to standard and high relative humidity conditions, respectively. Paper substrate apparent density results were calculated using the basis weight and thickness (caliper) results at standard laboratory conditions.

The standard deviation of the individual SCT results for the same paper sample was found to be on average about 8.06% of the mean, which was greater than the standard deviation of the RCT individual results (on average – 3.87% of the mean for the same paper sample). This confirms the recent claims in literature (Frank, 2003 & 2007) recommending the necessity to measure SCT on a large number of testing strips to ensure consistent and representative results. Therefore the employed standard testing methods for SCT and RCT ensured sufficient number of testing strips to generate statistically significant average results per paper sample. However, this should be considered for Quality control at paper mills and corrugating plants, when drafting the appropriate testing procedures. At the same time, the standard deviation of the ECT individual results was on average about 3.79% of the mean for the same board sample, with marginally larger variation in the results for the single wall boards.

The take up factors for the different fluting profiles for each corrugating plant were determined, and are also shown in Table A5 in Appendix 5. Only small differences are evident between the take up factors of the same flute profiles for the different corrugating plants.

The moisture content results of the randomly selected papers at the two different conditions are shown as percentages in table A5. It can be seen that the equilibrium moisture content of the selected papers at standard laboratory conditions is much lower than their equilibrium moisture content at high relative humidity, which is in agreement with the reviewed in paragraph 2.3.1. studies. The observed small differences in moisture content at the same climatic conditions for the different paper samples confirm that the equilibrium moisture content is also papermaking furnish dependent.

4.2. Calculated board compression strength results

The Maltenfort model (6), as discussed in paragraph 2.1.2.2. and shown again below in the form applicable for double wall board, was used to estimate the ECT of the corrugated boards:

$$ECT_{Calculated} = (\sigma_{c,L1} + \sigma_{c,L2} + \sigma_{c,L3} + \alpha_1\sigma_{c,F1} + \alpha_2\sigma_{c,F2}) \qquad (9)$$

Where σ_c is still the measured compression strength (using SCT or RCT) of the liners and fluting(s) medium papers used for the construction of the board, and α is the so called take-up factor(s), as indicated above.

Two calculations for each board were performed, using the SCT and RCT paper substrate results. The obtained results are shown in table A6 in Appendix 5 and compared to the measured ECT results. The annotations ECT_{SCT} and ECT_{RCT} refer to the results obtained by the above Maltenfort model, using the paper substrates' SCT and RCT results, respectively. The annotations 1 and 2 refer to the results obtained after exposure to standard and high relative humidity conditions, respectively, as indicated earlier.

4.3. Mathematical models correlating compression strengths of board and its components

In order to determine the linear regression constants in the Maltenfort model, correlating the measured ECT with the predicted ECT, using the paper components' compression strengths, the results from table A6 were plotted in figure 16.

The predictive mathematical models obtained by linear regression, using all data generated after exposure to the two climatic conditions for all corrugating plants, are as follows:

$$ECT = 0.6855\,(SCT_{L1} + SCT_{L2} + SCT_{L3} + \alpha_1 SCT_{F1} + \alpha_2 SCT_{F2}) + 0.0598 \quad (10)$$
$$R^2_{SCT} = 0.9719$$

$$ECT = 0.9685\,(RCT_{L1} + RCT_{L2} + RCT_{L3} + \alpha_1 RCT_{F1} + \alpha_2 RCT_{F2}) + 0.3462 \quad (11)$$
$$R^2_{RCT} = 0.9468$$

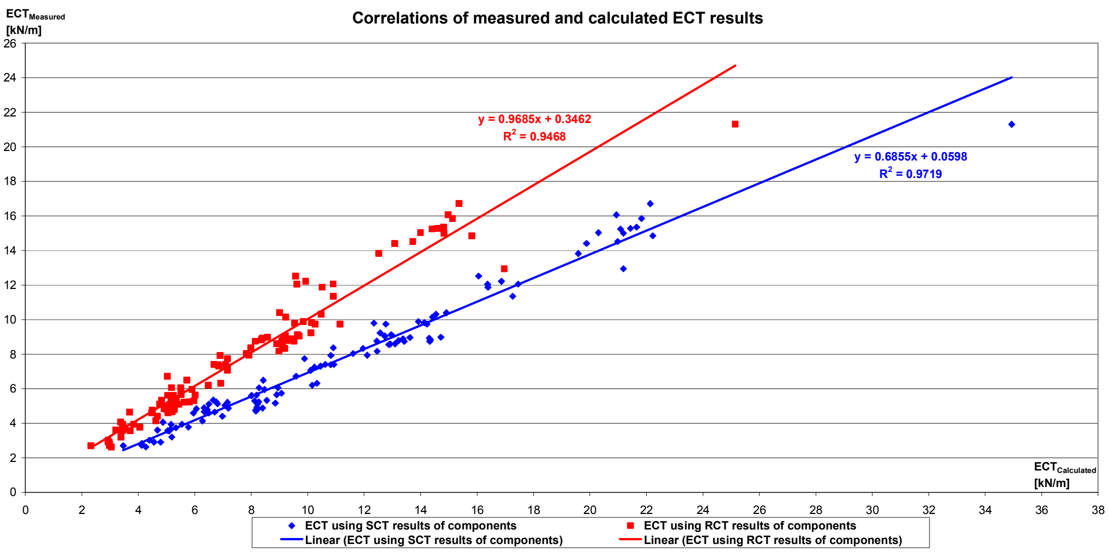


Figure 16. Calculated (using paper components' SCT and RCT results) vs. measured (using FEFCO No.8 method) ECT results.

The high coefficients of determination (**R^2**) suggest good correlation between the measured and predicted ECT results. However, the model (10) using the SCT results of the paper components, show somewhat better linear fit of the data (R^2_{SCT} = 0.9719). This could be the result from the limitations in the different paper compression strength testing methods, which have already been discussed widely in paragraph 2.2.1. It must also be noted that the FEFCO No 8 method used for this study to measure ECT has its limitations too, as shown in paragraph 2.2.2. Figure 7 in this report showed already that ECT results of stronger boards (ECT ≈> 10kN/m) could be up to 30% lower than the FPL Neck-Down method, which is widely accepted as the most accurate. The lower ECT results on the stronger boards when using the FEFCO method are mainly due to board edge failure, as reported in literature and reviewed in paragraph 2.2.2. During the laboratory testing, this limitation of the method was observed. Two distinct failure modes of two test specimens of the same corrugated board are shown in figure 17.

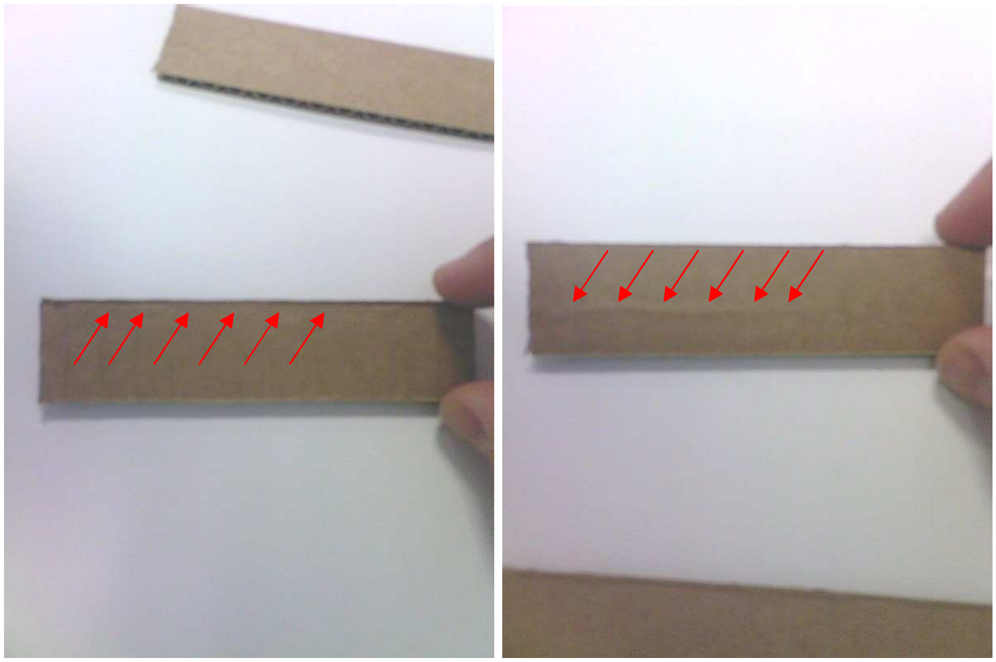


Figure 17. Difference in board failure under compression when using FEFCO No.8 ECT test method. Edge failure – left. Compression failure - right.

Based on the above results and observations, the data generated was used to determine whether better predicting linear mathematical models could be obtained. The results of the different paper and board combinations were separated into groups, depending on the board type, measured Edgewise compression strength and humidity exposure. The obtained linear mathematical models and their coefficients of determination (**R^2**) are shown in table 3.

From the results in table 3, it can be seen, that regardless of the group type selected, the models using SCT data showed consistently better prediction of ECT (one exception – group 7), based on the marginally higher coefficients of determination (R^2).

From the R-squared values it can be seen that the best fits were obtained using group 8 boards, which includes all board combinations results after exposure to the two climatic conditions, but excluding the results of Sample 2 (Appendix 5). The results of this extremely strong board impose some non-linearity in the data fit, as can be seen in figure 16. This was an isolated sample in this high strength range and additional samples of similar strength and board construction could not be obtained.

Table 3. Linear mathematical models for different board groups and exposure conditions.

Group type	Model using SCT results of paper components	R^2	Model using RCT results of paper components	R^2
1. All board types after standard and high humidity exposure	Y = 0.6855x + 0.0598	0.9719	Y = 0.9685x + 0.3462	0.9468
2. All board types after standard climate exposure	Y = 0.7184x - 0.5603	0.9657	Y = 0.9553x + 0.8103	0.9422
3. All board types after high humidity exposure	Y = 0.6798x + 0.2596	0.9682	Y = 0.8588x + 0.6660	0.9515
4. Single wall boards after standard and high humidity exposure	Y = 0.6046x + 0.5329	0.9560	Y = 0.9436x + 0.3110	0.9452
5. Double wall boards after standard and high humidity exposure	Y = 0.6389x + 1.1375	0.9577	Y = 0.8628x + 1.8074	0.8749
6. All board types having measured ECT > 10kN/m	Y = 0.5687x + 2.6624	0.8952	Y = 0.6494x + 5.2518	0.8235
7. All board types having measured ECT < 10kN/m	Y = 0.6542x + 0.2634	0.9448	Y = 0.9246x + 0.4448	0.9514
8. All board types after standard and high humidity exposure, excl. Sample 2*	Y = 0.7157x – 0.2298	0.9765	Y = 1.0461x - 0.1613	0.9629

***See tables A5 and A6 in Appendix 5 and refer to figure 16. Very high strength double wall board was excluded**

The SCT and RCT models of group 8 also show Y-intercepts approaching 0. As already discussed in paragraph 2.1.2.2., Y-intercept cannot be explained physically, i.e. if no compression is provided by the paper components, the board should have no compression strength. Therefore the linear fits of group 8 were forced through the origin and the results are shown in figure 18.

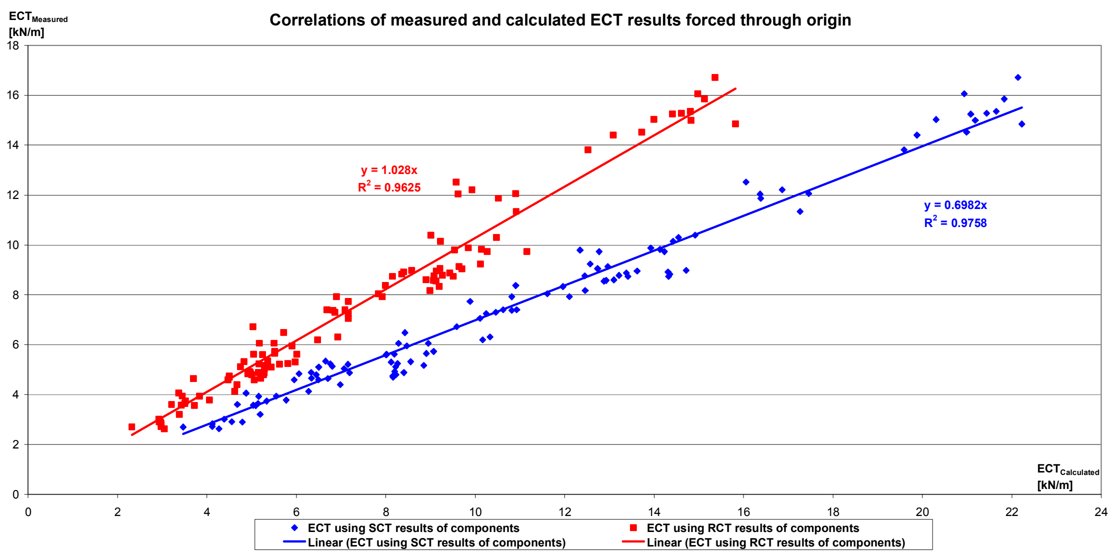


Figure 18. Calculated vs. measured ECT results of all board types (excl. sample 2) after exposure to the two climatic conditions. Linear fits forced through the origin.

The obtained predictive mathematical models are as follows:

$$\mathbf{ECT = 0.6982\,(SCT_{L1} + SCT_{L2} + SCT_{L3} + \alpha_1 SCT_{F1} + \alpha_2 SCT_{F2})} \qquad \mathbf{(12)}$$

$$\mathbf{R^2_{SCT} = 0.9758}$$

$$\mathbf{ECT = 1.028\,(RCT_{L1} + RCT_{L2} + RCT_{L3} + \alpha_1 RCT_{F1} + \alpha_2 RCT_{F2})} \qquad \mathbf{(13)}$$

$$\mathbf{R^2_{RCT} = 0.9625}$$

where the ECT, SCT and RCT are in kN/m, the correlating constant (**k**) is dimensionless and α is the profile and plant specific flute take up factor.

It can be seen that the new coefficients of determination are still very high and similar to the R-squared values of group 8 models from table 3.

In paragraph 2.1.2.2. it was indicated that theoretically the constant **k** in the predictive model under consideration should always be equal to unity. It can be seen that the obtained model (13), using the RCT results of paper components, satisfies this. However, the obtained value of close to unity in the above model, only shows that RCT results better predict the ECT results when using the FEFCO No.8 method. However, the limitations in the test methods are still valid and should be considered in any future work or practical applications of the models.

The obtained mathematical models are comparable to the models reported in literature (see Appendix 1). It must be noted that most of the cited in table A1 (Appendix 1) models correlate paper and board compression properties measured using different laboratory standard methods. Also most of the reported methods were developed for single wall boards and no data was available for double wall boards.

In figure 19, the linear fits of the overall data set, used for the predictive models (12) and (13), were compared to the linear fits of the results when separated depending on the exposure to the two climatic conditions. The close and almost overlapping linear fits confirm that the two models (12) and (13) can be used successfully to predict the compression strength of corrugated board using the measured paper compression strength (SCT and RCT) after exposure to any climatic condition. This can be further extrapolated to predict indirectly the final corrugated box stacking performance by measuring the paper substrate properties at any climatic conditions under consideration.

Further, the linear fits of the results for the two board types (single and double wall), encountered in the investigation, were forced through the origin and also compared to the overall data linear fits. Figure 20 shows the obtained graphical results, supporting the claim that the established predictive models (12) and (13) can be also used successfully to predict the ECT of single and double wall corrugated board constructions, using the measured paper compression strength (SCT and RCT).

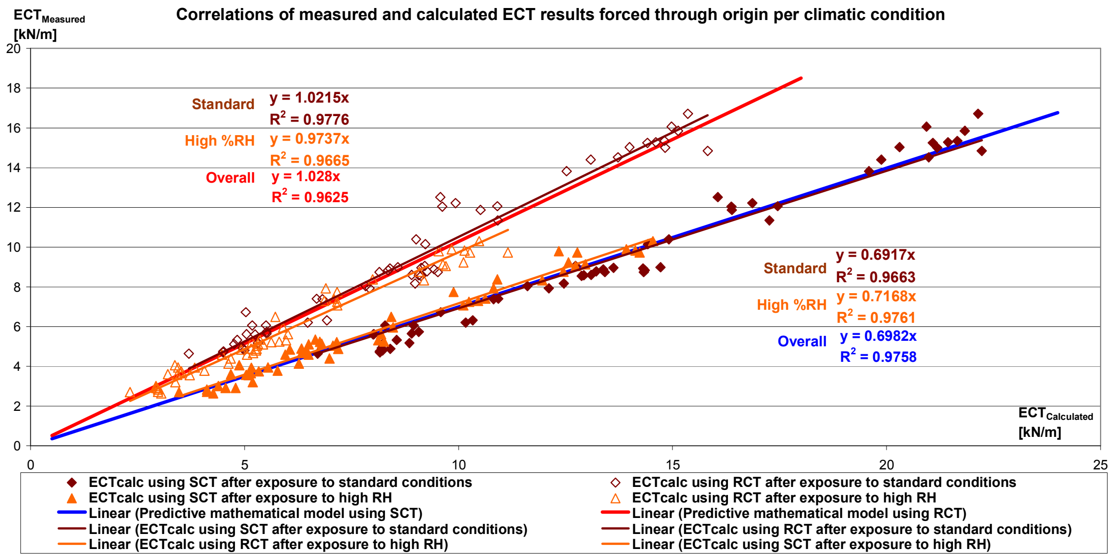


Figure 19. Calculated vs. measured ECT results divided into two sets – after exposure to standard, as well as high RH conditions, for all corrugators, including all board types (excl. sample 2). Linear fits forced through the origin. Correlation linear fits of all results as per figure 18 also included for comparison.

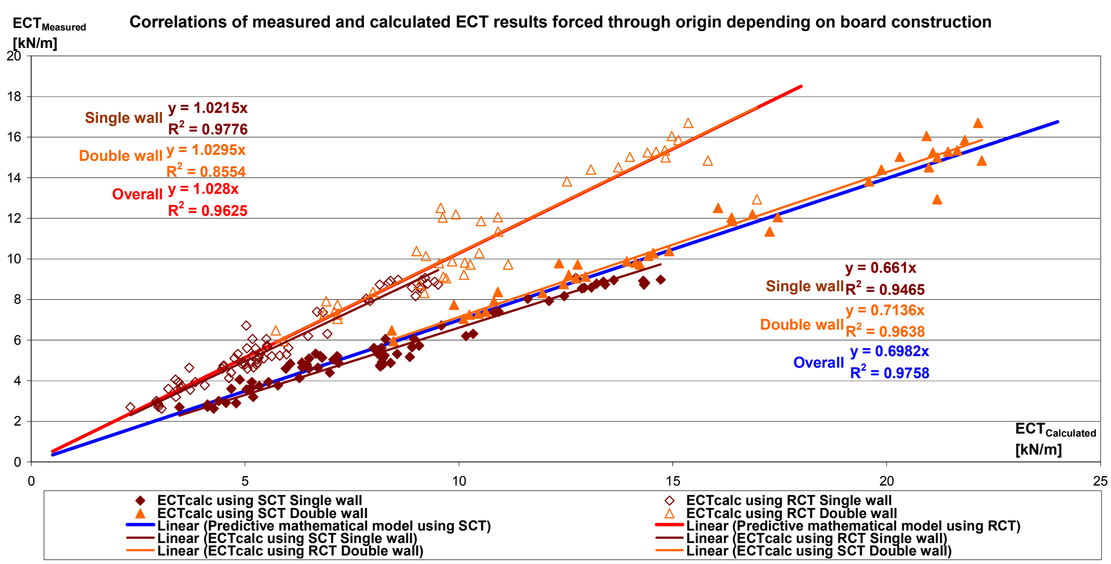


Figure 20. Calculated vs. measured ECT results divided into two sets – single and double wall board for all corrugators, after exposure to the two climatic conditions (excl. sample 2). Linear fits forced through the origin. Correlation linear fits of all results as per figure 18 also included for comparison.

4.4. Mathematical models – corrugating plants specific

It was also of interest for this study to determine whether the models obtained for the participating corrugating plants differ. Any differences could be attributed to plant process capabilities, manufacturing variables, negative impact on paper substrates, etc., as already discussed in paragraph 2.1.2.2.

The corrugating plant specific data plots and their linear fits are shown in figure 21. In the figure, it can be seen that the three sets of plant specific linear fits of the data almost overlap each other. Table 4 shows the plant specific predictive mathematical models, compared to the overall linear models. The linear fits again include all results after exposure to the two climatic conditions for all board types, they were also forced through the origin and the sample 2 results were excluded from the data set of Corrugator 1.

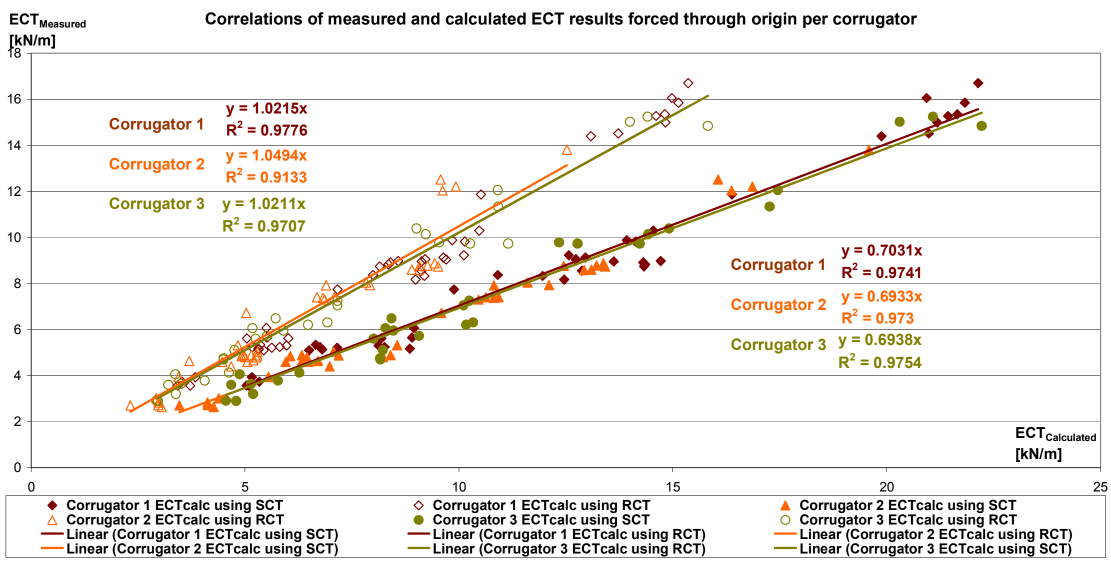


Figure 21. Calculated vs. measured ECT results per corrugating plant, including all board types (excl. sample 2) and after exposure to the two climatic conditions. Linear fits forced through the origin.

The RCT predictive model for Corrugator 2 shows somewhat lower R^2-value, but this could be attributed to some experimental error. Other than this, it can clearly be seen that no major difference exists between the plants' capabilities to convert the paper compression strength into corrugated board edgewise crush strength. As the overall work was conducted over the period of a few months, these results also indicate the consistency, quality and validity in experimental design, methods and equipment utilized.

Table 4. Linear mathematical models for the different corrugating plants, compared to overall models.

Plant	Model using SCT results of paper components	R^2	Model using RCT results of paper components	R^2
All corrugators	***Y = 0.6982x***	***0.9758***	***Y = 1.0280x***	***0.9625***
Corrugator 1	Y = 0.7031x	0.9741	Y = 1.0215x	0.9776
Corrugator 2	Y = 0.6933x	0.9730	Y = 1.0494x	0.9133
Corrugator 3	Y = 0.6938x	0.9754	Y = 1.0211x	0.9707

The results suggest that a single set of predictive mathematical models can be utilized with good degree of confidence in the industry. If certain negative deviations from these benchmark models are observed, efforts should be focused on investigating the cause for inefficiencies. If certain improvements in converting processes and equipment are implemented, these benchmark models can be used to quantify the benefits.

4.5. RCT vs. SCT

As already widely discussed in paragraph 2.2.1.7. of this report, many studies have been undertaken to compare and determine, whether to use the RCT or the SCT method for paper quality development and control. The published literature reports contradictory results with some preference towards the Short span compression test. Even though somewhat higher correlation when using SCT results was obtained, the comparative results between the two methods in this study could only confirm that good correlations with the boards' ECT results exist, regardless of the paper test method used. However, the linear correlations are different ($\mathbf{k_{SCT}}$ = 0.6982 vs. $\mathbf{k_{RCT}}$ = 1.028), confirming the existence of certain test method differences. This implies that plants can use either of the two paper test methods for quality control and development, but consider the difference in correlation to board strength performance.

Figure 22 shows the linear correlation between the SCT and RCT results obtained in this study. R^2 of 0.9166 suggests somewhat limited correlation between the results of the two test methods.

In addition 95% confidence intervals for some representative measured values were also included in figure 22. From the graphical representation, it can be seen, that the deviations between the two tests from the line of best fit are mostly due to underlying paper properties, affecting RCT and SCT differently, rather than the uncertainties in the measurements. This is especially evident in the lower compression strength results range, obtained from lighter and thinner papers, having lower stiffness.

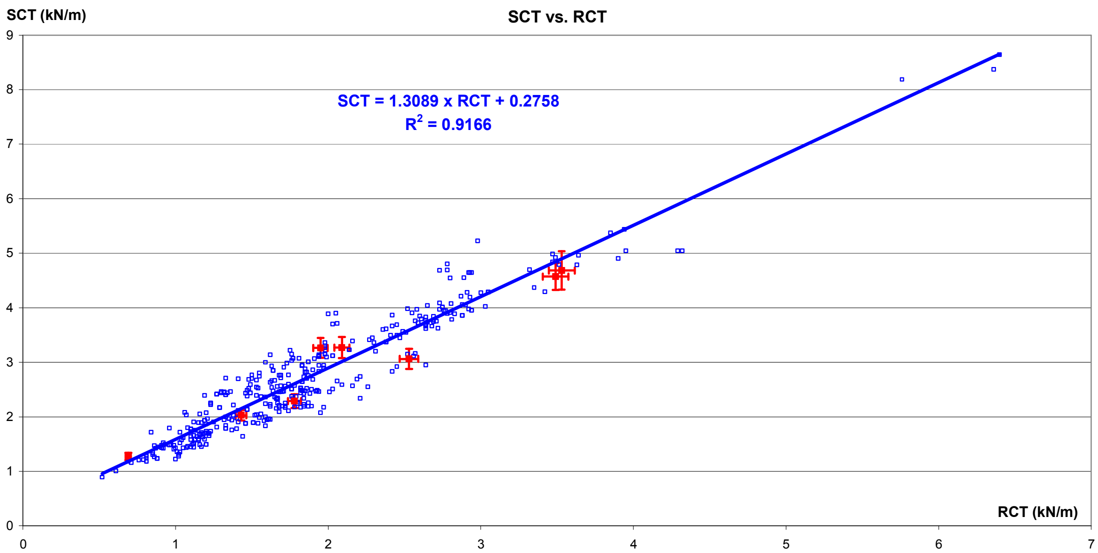


Figure 22. SCT vs. RCT linear fit obtained using the results for all papers tested after exposure to the two climatic conditions, including 95% confidence intervals for some representative measured values

4.6. Strength reduction after exposure to high humidity

As indicated in paragraph 4.3., the obtained predictive mathematical models can be used successfully to predict the compression strength of corrugated board using the measured paper compression strength (SCT and RCT) after exposure to any climatic condition. This implies that the reduction in paper compression strength measured by any of the two testing methods (SCT and RCT), could be translated to a reduction in the measured edgewise crush strength of the corrugated board. As the test results' correlations are different, it is expected to see different strength reduction results between the different test methods. Even though the strength reduction obtained using the results of the different test methods is not the same in magnitude, the loss in the board's compression strength is consistent with the loss in strength of its components.

The results in table A7 in Appendix 6 show the % reduction in ECT, SCT and RCT of all boards and papers after exposure to high humidity. They confirm the above expectations of different, but consistent, reduction in the measured strength, when using the test methods under consideration.

Table 5 shows the average reduction in paper components' SCT and RCT, as well as in boards' ECT, after exposure to high relative humidity conditions. As cited in paragraph 2.3.2.2., Byrd (1984) reported that after exposure to somewhat similar environmental conditions, the reduction in compressive strength of linerboard and medium was about 56% and the corrugated board made of the same papers lost about 60% of its edgewise compression strength. However, the test methods used were different – FPL Lateral support for the papers and the waxed edges TAPPI T811 for the boards (Byrd & Koning, 1978).

Somewhat similar results to the ones in table 5 were obtained by Whitsitt and McKee (1972), who reported losses in edgewise compression strength of around 43% after exposure to 85%RH at 73°F, but the authors did not report the test method used in their evaluation. As it was shown in figures 11 and 12, Van Eperen and Robbins (1994) reported reduction of about 40% and 32% in SCT and RCT, respectively, after the different papers were exposed to 80%RH at 23°C, which is consistent with the results obtained in this study.

Table 5. Average percentage reduction in SCT and RCT results after exposure of samples to high relative humidity conditions. For reference the reduction in ECT of the board was 39.2%

Test method	**Average reduction in compression strength of paper components**				
	Liner 1	Flute 1	Liner 2	Flute 2*	Liner 3*
ΔSCT	44.8%	41.0%	42.7%	37.8%	39.0%
ΔRCT	37.2%	32.8%	34.9%	31.9%	32.8%

***Only double wall board types**

From the results generated in this study a few additional observations can be made. As these findings fall outside the objectives of this study, they will only be outlined here and could be used to initiate further research in future:

- The reduction in compression strength (SCT and RCT) after exposure to the same conditions is different for different papers (see table A7 in Appendix 6). However, the combined effect of the different reduction in strength of the components is reflected in the board's ECT reduction, which supports the conclusions already made above;
- In table 5, it can be seen that the average reduction in flute SCT and RCT is lower than the average reduction in linerboards' strength.
- The reduction in strength of Flute 2 and Liner 3 is on average lower than Liner 1 and 2, and Flute 1.

The above difference in strength reduction after exposure to high humidity could be somewhat related to the different paper grades and their furnish composition. Even though Van Eperen and Robbins (1994) reported in their study no significant difference in paper compression performance at high humidity conditions for papers of different types or obtained from different sources, the results in this study clearly show different strength reduction between papers. The results in table A7 (Appendix 6) do not show the paper grades and their furnish composition, as this differentiation was outside the scope of this study. However, without referring to specific paper manufacturers and their products, it was evident that Liner 1 on average showed the highest reduction in SCT and RCT. Papers used in Liner 1 position were often white top linerboards, which indicates somewhat poorer performance of these papers after exposure to high humidity conditions, increasing the average SCT and RCT reduction for Liner 1. Further, for single wall boards, often the fluting grade used had recycled fiber furnish, compared to the double wall boards. Double wall boards are often used for corrugated boxes requiring high stacking strength. These boards were mostly made with fluting grades made of semi-chemical furnish, thus the lower average reduction in SCT and RCT of Flute 2 compared to Flute 1. This differentiated performance of the semi-chemical fluting grades contributes to the observed difference in strength reduction between the liners and the flutings average results. Most of the double wall boards in this study were also constructed using high performance virgin linerboards, compared to the single wall boards, where often linerboards made of recycled fiber furnish are utilized. The differentiated performance at high humidity of these high performance virgin linerboard grades is evident from the SCT and RCT average results, when comparing Liner 1 and 2, against Liner 3 in table 5.

These observations could explain the stated above points, but as indicated earlier, further research is recommended to investigate and confirm these findings.

5. Conclusions

The extensive literature investigation indicated that the compression strength of any corrugated board box is a direct measure of its stacking strength. Box stacking life depends in part on the perimeter of the box, as well as on the combined board edgewise compression strength and its flexural rigidity. In general, the higher the edgewise compression strength and flexural rigidity of the corrugated board, the higher the box stacking strength, with the first having much larger influence, as expressed by the McKee equation (1).

The relationship between the corrugated board edgewise compression strength (ECT) and its components' characteristics can be analyzed in many ways. Some of the reported in literature relationships between paper and board properties have become progressively more complex as the models have been refined to take into account all of the important structural and component characteristics. These models can be used for detailed research and development purposes, but they are too complicated for practical use.

A more useful approach to predict the compression strength of the corrugated board is to sum the compressive strengths of the linerboards and medium making up the corrugated board, allowing for the draw of the medium. This approach gives good predictive accuracies, if based on appropriate statistical weighting factors. The general format of this mathematical model is given by the so called Maltenfort equation:

$$\mathbf{ECT = k\,(\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F})}$$

The constant **k** is dependent on the paper and board compression strength test methods used, as well as on the impact from manufacturing variables at the corrugating plants.

The FPL Neck-Down test method resembles best the failure of the corrugated board under pure compression, but this method is somewhat difficult to be used in manufacturing environment and commercially available equipment for sample preparation is limited. Therefore the more user-friendly and widely spread FEFCO No. 8 (ISO 3037:1994(E)) was utilized in this investigation, knowing its limitations.

In order to develop a representative mathematical model correlating the compression strengths of board and its components, adequate paper and board compression strength test methods should be selected. The two most widely used paper compression strength test methods in the industry are the Ring crush test (RCT) and the STFI Short-span compression test (SCT). Certain limitations regarding the Ring crush testing method exist, pointing out that this method does not measure the true intrinsic edgewise compressive strength. Preferences were given in literature to the use of the STFI Short-span compression test.

As boxes are generally being transported at different climatic conditions stacked on top of each other, when environmental conditions change, the compression strength of the boxes changes. A corrugated box loses 50-60% or more of its short-term top load box compression strength when the relative humidity is increased from 50 to 90%. The major factor affecting the stacking performance of corrugated containers is the moisture content of the board. The equilibrium moisture content of paper is dependent on the ambient temperature and relative humidity among other factors. Moisture and temperature are perhaps the most important environmental variables affecting the strength properties of paper and board. As moisture content increases, ultimate paper strength properties are reduced, due to a reduction in inter-fiber bonding rather than fiber tensile strength. Corrugated board loses about 60% of its initial strength, when the relative humidity is increased from 50 to 90%. For the same change in climatic conditions, paper loses about 32% to 55% of its compression strength, depending on the test method used to measure the strength. The reduction in compression strength of paper, board and the final box product are correlated, but the reduction is dependent on the testing methodology employed.

The above literature findings indicated that by selecting suitable paper and board compression strength testing methods, reliable predictive mathematical models can be established. The mathematical models should be able to correlate board performance at any climatic conditions, by measuring the paper properties at these conditions. This can further be extrapolated to predict indirectly the final corrugated box stacking performance at the anticipated climatic conditions.

It must be noted that the compressive strength of a material does not accurately predict the compressive creep performance for any environmental condition. It had been reported that under cyclic humidity conditions, creep rate is faster than it is at any constant humidity level. This phenomenon is known as accelerated creep. Unlike the compressive strength tests, creep tests allow the material to deform and distribute the stresses in an optimal manner. However, the scope of this study was limited to the evaluation of the short-term compression strength of corrugated board and its components after exposure to certain environmental conditions, thus moisture-accelerated creep behaviour of paper and its derivatives was only noted.

The experimental work conducted in this investigation and the results generated were used to determine the linear regression constants in the Maltenfort model, correlating the measured ECT with the predicted ECT, using the paper components' compression strengths, measured using the SCT and RCT methods. The obtained predictive mathematical models are as follows:

$$\mathbf{ECT = 0.6982\ (SCT_{L1} + SCT_{L2} + SCT_{L3} + \alpha_1 SCT_{F1} + \alpha_2 SCT_{F2})}$$
$$\mathbf{R^2_{SCT} = 0.9758}$$

$$\mathbf{ECT = 1.028\ (RCT_{L1} + RCT_{L2} + RCT_{L3} + \alpha_1 RCT_{F1} + \alpha_2 RCT_{F2})}$$
$$\mathbf{R^2_{RCT} = 0.9625}$$

where the ECT, SCT and RCT are in kN/m, the correlating constant (**k**) is dimensionless and α is the profile and plant specific flute take up factor. The models showed very high coefficients of determination, which confirmed that the two models can be used successfully to predict the compression strength of any type of corrugated board, using the measured paper compression strength (SCT and RCT) after exposure to any constant climatic condition. These predictive mathematical models are comparable to similar models reported in literature.

It was also of interest for this study to determine whether the models obtained for the participating corrugating plants differ. The results indicated that the plant specific predictive mathematical models compared well to the overall linear models and that no major difference exists between the plants' capabilities to convert the paper compression strength into corrugated board edgewise crush strength. These results suggested that a single set of predictive mathematical models can be utilized with good degree of confidence in the South African industry. If certain negative deviations from these benchmark models are observed, efforts should be focused on investigating the cause for inefficiencies. If certain improvements in converting processes and equipment are implemented, these benchmark models can be used to quantify the benefits.

The models would allow packaging technologists in the field to select adequate paper substrates, with certain strength characteristics, to manufacture corrugated board with the necessary compression strength for achieving a desired carton performance for certain climatic condition.

One of the objectives of this study was to compare the board strength predictability when using the RCT or the SCT paper test methods. Even though somewhat higher correlation when using SCT results was obtained, the comparative results between the two methods in this study could only confirm that good correlations with the boards' ECT results exist, regardless of the paper test method used. This implies that plants can use either of the two paper test methods for quality control and development, but consider the difference in correlation to board strength performance. The linear correlation between the SCT and RCT results obtained in this study, suggested somewhat limited correlation between the results of the two test methods:

$$\mathbf{SCT = 1.3089 \times RCT + 0.2758}$$
$$\mathbf{R^2 = 0.9166}$$

The results in this study showed that the reduction in compression strength (SCT and RCT) after exposure to the same conditions is different for different papers, but the combined effect of the board's components is reflected in the board's ECT reduction. It was speculated that the difference in strength reduction after exposure to high humidity could be somewhat related to the different paper grades and their furnish composition. In general high performance virgin linerboards and semi-chemical fluting papers showed lower reduction in SCT and RCT after exposure to high humidity conditions. However, these observations suggest the need to conduct further research in this area in order to investigate the fundamentals behind these findings.

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Appendix 1

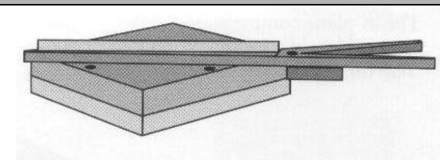
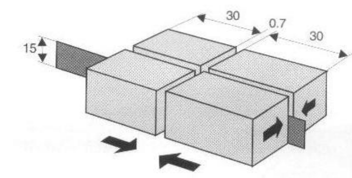
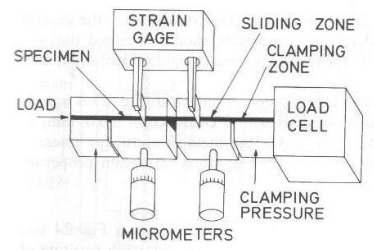
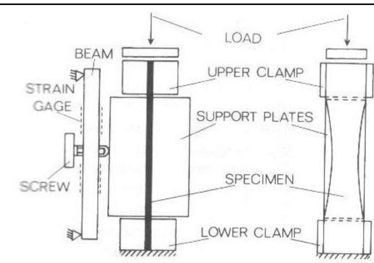
Table A1. Summary of literature reviewed mathematical models correlating board ECT and paper properties.

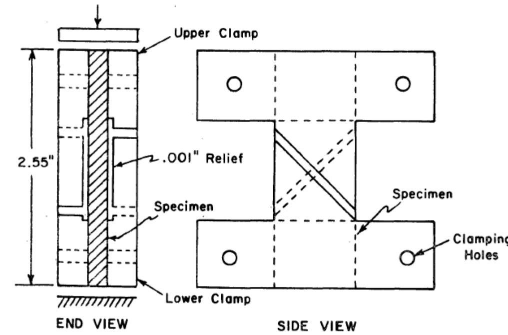
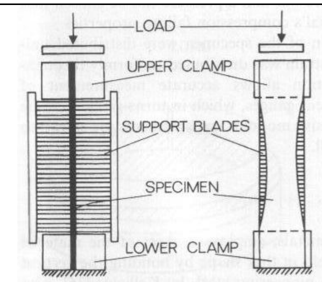
Mathematical model	Comments	Author(s)
ECT = 0.646 $(2 \times \sigma_{Liner})^{0.845} P_{cr}^{0.155} + \alpha\sigma_{medium}$ If $\sigma_{Liner} \geq P_{cr}$, liner buckling occurs $P_{cr} = \frac{4\pi^2\sqrt{D_{11}D_{22}}}{Kb_f^2}$ ECT = 0.695 $(2 \times \sigma_{Liner} + \alpha\sigma_{medium})$ If $P_{cr} \geq \sigma_{Liner}$, liner buckling does not occurs	P_{cr} is the critical buckling load per unit width α is the fluting take up factor σ is the intrinsic paper compression strength, measured using SCT method $(D_{11}D_{22})^{1/2}$ is the geometric mean (MD-CD) flexural rigidity of a plate b_f is the flute spacing K is a constant depending on the restraint to rotation, appears to be around 1 from observations	Popil, Coffin & Kaewmanee (2004)
ECT = $(2E_y t_f/K_1G) + (\alpha E_y t_{cm}/K_1G)$ $G = \frac{12}{K_2\pi^2}\left(\frac{b_f}{t_f}\right)^2$ When assuming that the stress-strain properties of the corrugating medium are the same as that of the linerboards	t_f is the facing thickness, in α is the fluting take up factor t_{cm} is the corrugating medium thickness, in E_y is the modulus of elasticity of liner in CD, psi K_1 is a parameter K_2 is a buckling coefficient (Moody, 1965), dependent on the ratio of the thickness of the corrugating medium to the facing thickness and the flute-type b_f = distance between facing supports (flute tips), in	Koning (1975)
ECT = 0.685 $(2xS_l + D\ S_m)$ + 4.62 (ib/inch) ECT = 0.685 $(2xS_l + D\ S_m)$ + 0.809 (kN/m)	***ECT*** is board edge crush, lb/inch or kN/m S_l is the SCT_{CD} result of linerboard, lb/inch or kN/m S_m is the SCT_{CD} result of medium, lb/inch or kN/m D is the draw or take-up factor of the fluting medium	Whitsitt & Baum (1985)
ECT = 0.80 (L+DM) + 12.0 (ib/inch)	***ECT*** is board edge crush determined by the TAPPI method,	Van Eperen &

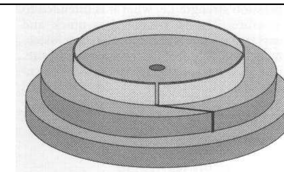
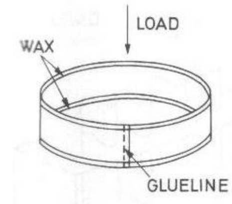
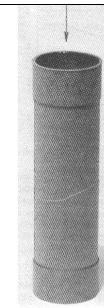
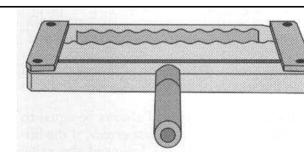
for single wall board grades through 200 psi ECT = 0.80 (L+DM) + 2.102 (kN/m) ECT = 1.27 (L+DM) – 6.0 (ib/inch) for single wall board grades of 250 psi and above ECT = 1.27 (L+DM) – 1.051 (kN/m)	lb/inch or kN/m ***L+DM*** is the sum of the liners and medium RCT_{CD} results, lb/inch or kN/m ***D*** is the draw or take-up factor of the fluting medium	Sprague (1983)
$ECT = k\ (\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F})$ ***k*** depends upon measurement method of $\boldsymbol{\sigma_c}$: $\mathbf{k_{RCT}} = 1.28 \pm 0.08$ $\mathbf{k_{CCT}} = 0.97 \pm 0.04$ $\mathbf{k_{SCT}} = 0.71 \pm 0.03$	***ECT*** is board edge crush, determined by the FEFCO method $\boldsymbol{\sigma_c}$ is the compression strength in CD of liners (L_1 or L_2) and fluting medium paper (F) $\boldsymbol{\alpha}$ is the so called take-up factor as indicated above	Markstrom (1999)
$ECT = 1.302\ (RCT_{L1} + RCT_{L2} + \alpha RCT_F)$	***ECT*** is board edge crush, lb/inch or kN/m ***RCT*** is the ring crush compression strength in CD of liners (L_1 or L_2) and fluting medium paper (F) $\boldsymbol{\alpha}$ is the so called take-up factor as indicated above	Koning (1964)
$ECT = k\ (\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F})$ ***k*** depends upon corrugating plant and fluting type: $\mathbf{K_{Plant\ 1}} = 0.696$ (for C flute) $\mathbf{K_{Plant\ 1}} = 0.733$ (for B flute) $\mathbf{K_{Plant\ 2}} = 0.740$ (for C & B flute) $\mathbf{K_{Plant\ 3}} = 0.788$ (for C & B flute)	***ECT*** is board edge crush, determined by the TAPPI Test Method (T 811) $\boldsymbol{\sigma_c}$ is the compression strength in CD of liners (L_1 or L_2) and fluting medium paper (F) determined by the SCT method $\boldsymbol{\alpha}$ is the so called take-up factor as indicated above	Seth (1985)

Appendix 2

Table A2. Summary of literature reviewed available compression strength test methods for paper.

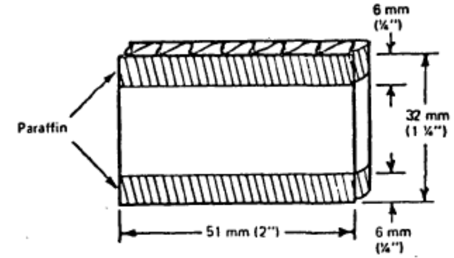
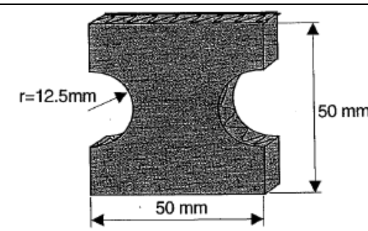
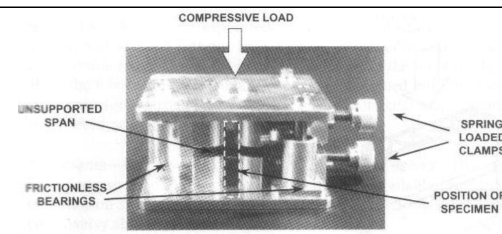
Driving principle	Method	Standard Testing Methods	Schematic presentation (Fellers & Donner, 2002)
Short-Span Specimen Geometry	Concora Liner Test - **CLT**	*n/a*	
	STFI Short-Span Test – **SCT**	*TAPPI T826* *ISO 9895:1989(E)*	
Plate-Supported Specimen	STFI Solid Support Test	*Not commercially available, only for R&D work*	
	PPRIC Plate Support Test	*Not commercially available, only for R&D work*	

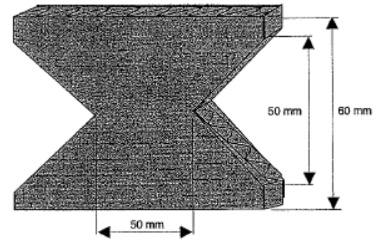
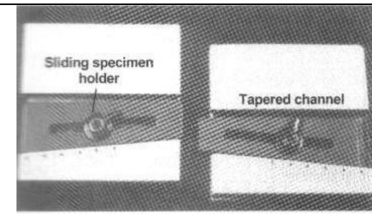
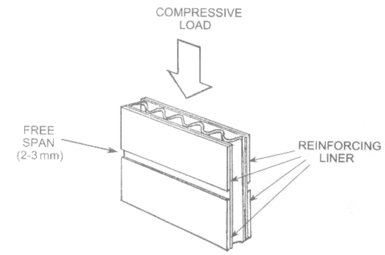
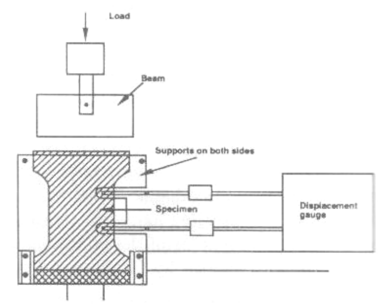
	FPL Lateral Support Test	*Not commercially available, only for R&D work*	
Blade-Supported Specimen	STFI Blade Support Test	*Not commercially available, only for R&D work*	n/a
	Weyerhauser Lateral Support Test	*Not commercially available, only for R&D work*	
	FPL Vacuum Restraint	*Not commercially available, only for R&D work*	n/a

Cylindrical Geometry	Ring Crush Test - **RCT**	*TAPPI T818* *TAPPI T822* *ISO 12192:2002(E)*	
	IPC-Modified Ring Crush Test	*n/a*	
	FPL Supported Cylinder Test	*n/a*	
Corrugated Specimen	Concora Fluted Crush Test – **CFC**	*n/a*	n/a
	H&D Stiffness Test	*n/a*	n/a
	Corrugated Crush Test - **CCT**	*TAPPI T824*	

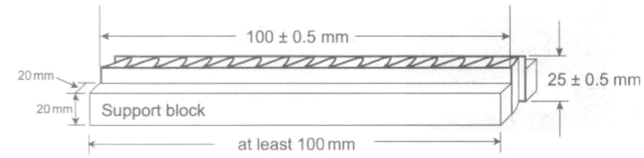
Appendix 3

Table A3. Summary of literature reviewed available edgewise compression strength test methods for board.

<table>
<tr><th>Driving principle</th><th>Method</th><th>Standard Testing Methods</th><th>Schematic presentation (Fellers & Donner, 2002)</th></tr>
<tr><td rowspan="3">Methods Avoiding Edge Failure</td><td>Wax reinforced edges</td><td>TAPPI T811</td><td></td></tr>
<tr><td>FPL Neck-Down specimen</td><td>TAPPI T838</td><td></td></tr>
<tr><td>Edge Clamping</td><td>TAPPI T839</td><td></td></tr>
</table>

	Japanese Industrial standard	*JIS Z-0401*	
	Morris clamping method	*TAPPI T841*	
	Reinforced Liners method	*n/a*	
	Long Span method	*n/a*	

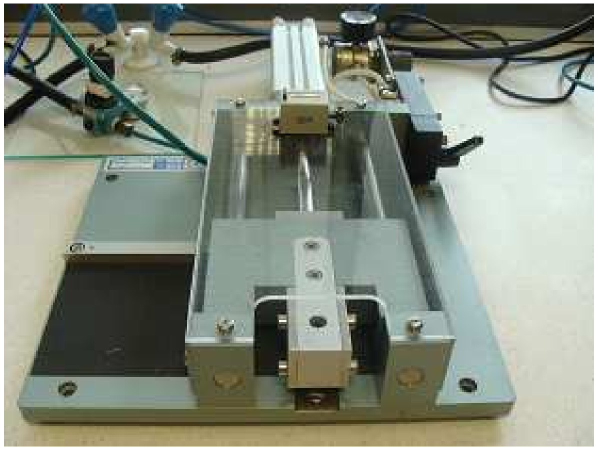
Methods Using Rectangular Specimen to Minimize Edge Damage	Rectangular Specimen method	*SCAN (P33:71)*	
		FEFCO (No. 8)	
		ISO 3037:1994(E)	



Appendix 4

Table A4. Apparatus available at Sappi Technology Centre and used for the experimental work.

 **TMI Precision micrometer**	 **Mettler AE200 Scientific scale**	 **W. Memment, Schwabach laboratory oven**
 **Hung Ta Environmental humidity chamber**	 **TMI Short span compression tester**	 **L&W Crush tester**



L&W ECT sample cutter

Guillotine (RCT)

Guillotines (SCT)

Appendix 5

Table A5. Paper substrate and corrugated board physical properties.

	Sample	Board		Liner 1									Fluting 1											Liner 2									Fluting 2											Liner 3								
		ECT_1	ECT_2	SCT_1	SCT_2	RCT_1	RCT_2	BW	Caliper	Density	$Moisture_1$	$Moisture_2$	SCT_1	SCT_2	RCT_1	RCT_2	BW	Caliper	Density	Profile	Take-up	$Moisture_1$	$Moisture_2$	SCT_1	SCT_2	RCT_1	RCT_2	BW	Caliper	Density	$Moisture_1$	$Moisture_2$	SCT_1	SCT_2	RCT_1	RCT_2	BW	Caliper	Density	Profile	Take-up	$Moisture_1$	$Moisture_2$	SCT_1	SCT_2	RCT_1	RCT_2	BW	Caliper	Density	$Moisture_1$	$Moisture_2$
		kN/m		kN/m				g/m^2	μm	kg/m^3	%		kN/m				g/m^2	μm	kg/m^3		α_1	%		kN/m				g/m^2	μm	kg/m^3	%		kN/m				g/m^2	μm	kg/m^3		α_2	%		kN/m				g/m^2	μm	kg/m^3	%	
Corrugator 1	1	14.40	8.37	3.696	1.880	2.64	1.54	203.1	250	812			3.360	2.000	1.98	1.33	160.2	255	628	E	1.29			3.777	1.929	2.69	1.58	226.0	303	746			3.263	1.904	1.98	1.25	159.8	255	627	B	1.31			3.796	2.024	2.61	1.52	204.5	255	802		
	2	21.30	12.94	8.642	5.045	6.40	4.32	393.2	545	721	7.55%	12.52%	3.496	2.225	2.45	1.62	178.5	310	576	C	1.41	7.68%	12.80%	8.189	4.903	5.76	3.90	394.1	550	717			3.666	2.331	2.42	1.66	175.1	305	574	B	1.31			8.373	5.042	6.36	4.29	391.5	550	712		
	3	15.00	9.04	3.897	2.429	2.78	1.84	179.1	245	731			3.200	1.987	2.31	1.55	175.2	315	556	C	1.41	7.31%	12.59%	4.040	2.359	2.65	1.65	179.1	252	711			3.568	2.196	2.49	1.7	173.3	302	574	B	1.31			4.059	2.270	2.88	1.80	172.9	248	697	7.26%	13.18%
	4	15.28	9.13	3.828	2.198	2.64	1.72	176.1	240	734			3.412	2.190	2.27	1.62	174.2	303	575	C	1.41			3.978	2.371	2.92	1.79	179.2	255	703			3.613	2.238	2.38	1.59	171.1	295	580	B	1.31			4.086	2.373	2.73	1.76	177.9	255	698		
	5	11.87	7.74	2.555	1.444	1.67	1.10	137.2	197	696	8.09%	12.49%	2.522	1.578	1.48	1.04	122.2	210	582	C	1.41	7.77%	12.40%	2.392	1.358	1.53	1.01	138.2	196	705			2.430	1.620	1.46	1.05	120.6	210	574	B	1.310	8.17%	12.31%	4.699	2.736	3.32	2.21	225.4	355	635	7.94%	11.51%
	6	5.17	3.56	2.662	1.460	1.63	1.08	138.0	179	771			2.769	1.674	1.50	1.16	124.8	206	606	B	1.31			2.562	1.439	1.72	1.12	140.1	198	708																						
	7	6.06	3.93	2.711	1.490	1.69	1.11	138.0	179	771			2.800	1.695	1.55	1.19	124.8	206	606	B	1.31			2.572	1.449	1.78	1.17	140.1	198	708																						
	8	5.65	3.74	2.528	1.421	1.54	0.92	139.5	179	779			2.984	1.891	1.73	1.17	124.1	210	591	B	1.31			2.468	1.436	1.71	1.07	138.0	201	687																						
	9	5.61	3.57	2.463	1.432	1.70	1.05	138.0	201	687			2.439	1.717	1.34	1.03	124.1	195	636	B	1.31			2.362	1.355	1.59	1.03	139.1	196	710																						
	10	8.83	5.13	4.691	1.959	2.78	1.61	197.2	248	795	6.69%	12.59%	3.898	1.975	2.05	1.40	160.2	271	591	B	1.31	7.62%	12.99%	4.554	2.257	2.89	1.87	224.3	311	721	7.67%	12.17%																				
	11	8.74	5.23	4.685	1.943	2.73	1.60	197.2	248	795			3.890	1.967	2.00	1.35	160.2	271	591	B	1.31			4.545	2.240	2.80	1.80	224.3	311	721																						
	12	8.98	5.10	5.226	2.153	2.98	1.66	202.3	256	790	6.28%	11.65%	3.699	1.643	2.03	1.44	158.8	265	599	B	1.31			4.647	2.195	2.94	1.89	226.5	323	701																						
	13	8.92	5.34	4.807	2.166	2.78	1.72	194.1	247	786			3.711	1.754	2.06	1.37	166.1	275	604	B	1.31			4.643	2.190	2.92	1.84	226.5	323	701																						
	14	8.96	5.21	4.784	2.588	3.63	2.09	247.0	310	797	7.25%	12.49%	3.200	1.812	1.96	1.27	158.1	250	632	B	1.31			4.644	2.192	2.93	1.87	226.5	323	701																						
	15	15.35	9.23	3.846	2.108	2.60	1.74	177.1	240	738			3.546	2.338	2.51	1.84	174.1	297	586	C	1.41			4.213	2.427	2.87	1.88	179.6	251	716			3.450	1.952	2.29	1.62	176.1	301	585	B	1.31			4.0725	2.180	2.805	1.78	175.4	251.5	697		
	16	14.52	8.33	3.687	2.210	2.45	1.68	178.1	249	715			3.361	1.966	2.30	1.61	173.2	298	581	C	1.41			3.984	2.250	2.52	1.67	182.5	244	748			3.597	2.052	2.36	1.56	178.1	305	584	B	1.31			3.864	2.038	2.42	1.53	176.2	248	710		
	17	15.85	9.82	3.946	2.491	2.76	1.82	182.2	250	729			3.733	2.642	2.65	1.83	180.4	298	605	C	1.41			3.904	2.344	2.55	1.67	182.3	253	721			3.721	2.481	2.59	1.83	178.6	293	610	B	1.31			3.839	2.322	2.69	1.67	175.2	252	695		
	18	16.71	10.30	3.972	2.519	2.73	1.86	179.3	258	695			3.733	2.642	2.65	1.83	180.4	298	605	C	1.41			4.014	2.525	2.75	1.82	177.0	259	683			3.721	2.481	2.59	1.83	178.6	293	610	B	1.31			4.014	2.525	2.75	1.82	177.0	259	683		
	19	16.06	9.88	3.888	2.439	2.83	1.82	199.0	261	762			3.492	2.454	2.41	1.68	174.2	295	591	C	1.41			3.750	2.459	2.69	1.69	201.5	266	758			3.375	2.366	2.38	1.56	177.9	310	574	B	1.31			3.952	2.466	2.94	1.92	199.2	262	760		
	20	8.55	5.30	3.939	2.334	2.76	1.77	179.7	247	728			3.665	2.509	2.64	1.76	178.1	301	592	C	1.41			3.770	2.251	2.64	1.72	181.6	251	724																						
	21	9.06	5.62	3.623	2.180	2.72	1.68	183.7	256	718			3.665	2.509	2.64	1.76	178.1	301	592	C	1.41			3.944	2.473	2.77	1.85	180.5	248	728																						
	22	8.17	5.24	3.952	2.466	2.94	1.92	199.2	262	760			3.375	2.366	2.38	1.56	181.3	293	619	C	1.41			3.750	2.459	2.69	1.69	201.5	266	758																						
Corrugator 2	1	5.32	3.01	2.933	1.477	1.63	0.99	135.2	169	800	7.25%	12.88%	2.438	1.240	1.30	0.81	129.6	198	655	B	1.33	7.37%	12.75%	2.380	1.261	1.47	0.86	136.1	178	765																						
	2	4.88	2.63	2.907	1.427	1.71	1.00	134.9	167	808			2.224	1.214	1.23	0.79	125.8	202	623	B	1.33			2.539	1.226	1.63	1.00	140.5	191	736																						
	3	4.64	2.70	2.634	1.275	1.62	1.02	142.8	197	725			1.716	0.893	0.84	0.52	108.8	231	471	B	1.33			1.791	1.006	0.96	0.61	122.5	229	535																						
	4	4.92	2.72	2.571	1.314	1.69	1.02	141.5	204	694			2.401	1.185	1.33	0.81	125.1	198	632	B	1.33	7.04%	12.49%	2.436	1.233	1.49	0.88	139.2	192	725																						
	5	8.78	4.89	3.663	1.780	2.68	1.40	200.5	253	792			3.096	1.503	1.99	1.12	162.9	250	652	B	1.33	7.09%	12.71%	5.436	2.551	3.94	2.26	306.1	410	747	7.86%	13.61%																				
	6	8.60	4.84	3.915	1.881	2.80	1.46	199.8	258	774			3.159	1.506	1.98	1.12	164.3	252	652	B	1.33			4.982	2.176	3.47	1.97	308.1	431	715																						
	7	4.80	2.83	2.595	1.314	1.74	1.02	140.0	198	707			2.401	1.185	1.33	0.81	125.1	198	632	B	1.33			2.436	1.233	1.49	0.88	139.2	192	725																						
	8	8.58	4.59	3.861	1.893	2.88	1.51	202.0	261	774			3.118	1.493	2.03	1.20	163.1	250	652	B	1.33			4.921	2.074	3.49	1.95	305.5	418	731																						
	9	8.88	4.79	3.861	1.893	2.88	1.51	202.0	261	774			3.118	1.493	2.03	1.20	163.1	250	652	B	1.33			5.370	2.568	3.85	2.16	308.0	420	733																						
	10	8.74	4.66	4.193	1.877	2.93	1.46	201.1	261	770			3.145	1.594	1.98	1.15	159.9	251	637	B	1.33			5.041	2.341	3.95	2.21	310.0	404	767																						
	11	13.82	8.76	3.786	2.173	2.81	1.82	252.2	311	811	6.93%	11.28%	2.998	1.967	1.59	1.21	122.9	202	608	C	1.44			4.283	2.692	2.91	2.19	222.6	331	673			2.698	1.901	1.41	1.12	122.9	210	585	B	1.33			3.615	2.225	2.64	1.84	226.1	312	725		
	12	12.52	7.92	3.070	1.773	1.77	1.10	133.8	165	811	6.99%	10.14%	2.413	1.434	1.27	0.91	124.8	200	624	C	1.44	6.95%	10.69%	2.821	2.116	1.86	1.41	158.4	266	595			2.485	1.799	1.47	1.08	123.1	209	589	B	1.33			3.387	2.472	2.16	1.64	164.7	266	619		
	13	12.21	7.40	3.070	1.773	1.77	1.10	133.8	165	811			2.413	1.434	1.27	0.91	124.8	200	624	C	1.44			3.109	2.133	1.94	1.47	156.5	261	600			3.109	2.039	1.94	1.42	156.8	270	581	B	1.33			3.074	1.943	1.81	1.32	160.3	255	629		
	14	6.72	3.94	3.139	1.727	1.62	1.10	131.5	170	774			2.706	1.420	1.33	0.87	127.3	205	621	B	1.33			2.850	1.933	1.64	1.19	144.8	210	690	7.56%	11.39%																				
	15	8.04	5.04	4.053	2.458	2.90	2.01	220.8	295	748			2.455	1.493	1.32	0.93	123.5	196	630	C	1.44			4.021	2.461	3.03	1.94	223.5	309	723																						
	16	12.04	7.30	3.070	1.773	1.77	1.10	133.8	165	811			2.413	1.434	1.27	0.91	124.8	200	624	B	1.33			3.109	2.133	1.94	1.47	156.5	261	600			3.109	2.039	1.94	1.42	156.8	270	581	B	1.33			2.850	1.933	1.64	1.19	144.8	210	690		
	17	7.38	4.59	3.007	1.751	1.87	1.13	134.0	174	770			2.446	1.450	1.32	0.89	125.3	203	617	C	1.44			4.288	2.656	3.05	2.06	201.3	233	864	7.20%	11.09%																				
	18	7.40	4.40	3.007	1.751	1.87	1.13	134.0	174	770			2.744	1.893	1.55	1.15	122.5	203	603	C	1.44			3.969	2.505	2.58	1.89	196.8	217	907																						
	19	7.93	4.87	4.288	2.485	3.05	1.93	221.3	305	726			2.460	1.525	1.30	0.92	122.9	202	608	C	1.44			4.277	2.507	3.00	2.03	222.4	300	741																						
Corrugator 3	1	5.60	4.06	2.701	1.653	1.86	1.22	163.3	271	603			2.049	1.208	1.16	0.76	129.2	224	577	B	1.28			2.684	1.676	1.90	1.18	158.2	293	540																						
	2	6.06	3.60	2.768	1.520	1.74	1.12	160.0	292	548			2.073	1.158	1.20	0.71	127.1	262	485	B	1.28			2.862	1.679	1.90	1.18	161.5	276	585																						
	3	12.06	7.25	3.220	1.872	1.75	1.20	142.7	201	710			2.890	1.690	1.97	1.22	165.6	274	604	C	1.41			3.265	2.025	1.95	1.38	144.9	197	736			3.228	1.788	2.14	1.33	168.8	299	565	B	1.28			2.763	1.676	1.69	1.16	141.7	205	691		
	4	11.34	7.06	3.029	1.735	1.76	1.20	144.4	209	691			2.890	1.690	1.97	1.22	165.6	274	604	C	1.41			3.265	2.025	1.95	1.38	144.9	197	736			3.228	1.788	2.14	1.33	168.8	299	565	B	1.28			2.763	1.676	1.69	1.16	141.7	205	691		
	5	10.14	6.49	2.832	1.707	1.94	1.20	158.2	285	555			2.167	1.278	1.29	0.81	133.7	219	611	C	1.41			2.822	1.568	1.85	1.15	156.3	285	548			2.217	1.341	1.38	0.85	132.7	206	644	B	1.28			2.878	1.634	1.85	1.14	163.0	286	570		
	6	10.39	5.95	3.151	1.843	1.76	1.33	141.9	199	713			2.167	1.278	1.29	0.81	133.7	219	611	C	1.41			2.822	1.568	1.85	1.15	156.3	285	548			2.465	1.303	1.36	0.85	128.7	218	590	B	1.28			2.731	1.589	1.84	1.19	162.7	294	553		
	7	14.85	9.73	4.965	3.149	3.64	2.52	250.2	348	719			3.127	1.938	1.94	1.37	158.6	251	632	C	1.41			4.371	2.832	3.35	2.42	249.7	333	750			3.270	2.028	2.09	1.43	157.7	259	609	B	1.28			4.293	2.921	3.42	2.45	252.1	335	753		
	8	15.03	9.79	3.757	2.000	2.57	1.59	207.7	260	799			2.759	1.584	1.68	1.10	162.9	292	558	E	1.24			4.793	3.160	3.51	2.57	252.4	348	725			2.937	1.685	1.829	1.16	157.5	307	513	B	1.28			4.572	3.062	3.49	2.53	252.2	336	751		
	9	15.25	9.73	3.450	1.833	2.47	1.59	200.4	253	792			3.135	1.906	1.94	1.41	158.0	256	617	E	1.24			4.836	2.949	3.47	2.64	249.9	342	731			3.300	1.966	1.98	1.35	157.2	261	602	B	1.28			4.684	3.111	3.53	2.56	251.4	338	744		
	10	4.70	2.90	2.702	1.521	1.50	1.03	138.6	242	573	6.86%	12.15%	2.034	1.271	1.07	0.69	126.2	223	566	C	1.41	6.62%	12.06%	2.592	1.480	1.49	0.96	139.9	237	590	6.83%	12.40%																				
	11	4.75	2.91	2.544	1.489	1.53	0.97	138.3	241	574	6.65%	12.06%	2.078	1.180	1.06	0.69	129.2	245	527	C	1.41	6.70%	11.75%	2.683	1.404	1.48	0.99	137.5	240	573	6.66%	11.82%																				
	12	6.20	3.78	2.947	1.628	1.83	1.18	166.2	304	547	6.11%	11.59%	2.945	1.708	1.94	1.17	166.0	296	561	C	1.41	6.27%	11.99%	3.066	1.736	1.91	1.23	157.3	281	560	6.30%	11.56%																				
	13	5.73	3.64	2.754	1.486	1.87	1.16	162.7	298	546	6.33%	11.73%	2.390	1.467	1.19	0.86	112.1	183	613	C	1.41	6.83%	11.82%	2.945	1.589	1.97	1.13	163.5	281	582	6.52%	11.80%																				
	14	6.31	4.13	3.752	2.092	2.71	1.68	205.6	253	813	6.44%	11.68%	2.250	1.479	1.23	0.91	111.1	192	579	B	1.28	7.52%	12.29%	3.700	2.287	2.64	1.78	180.2	244	739	7.24%	12.10%																				
	15	5.11	3.20	2.674	1.636	1.53	1.10	137.9	205	673	6.82%	12.08%	2.250	1.479	1.23	0.91	111.1	192	579	B	1.28			2.667	1.661	1.65	1.12	141.1	202	699	6.80%	12.16%																				

Table A6. Calculated board compression strength results, using the Maltenfort model.

	Sample	Board Measured		Board Calculated			
		ECT_1	ECT_2	ECT_{1SCT}	ECT_{2SCT}	ECT_{1RCT}	ECT_{2RCT}
		kN/m		kN/m			
Corrugator 1	1	14.40	8.37	19.88	10.91	13.09	7.99
	2	21.30	12.94	34.94	21.18	25.14	16.97
	3	15.00	9.04	21.18	12.74	14.83	9.70
	4	15.28	9.13	21.44	12.96	14.61	9.64
	5	11.87	7.74	16.39	9.89	10.52	7.16
	6	5.17	3.56	8.85	5.09	5.32	3.72
	7	6.06	3.93	8.95	5.16	5.50	3.84
	8	5.65	3.74	8.91	5.33	5.52	3.52
	9	5.61	3.57	8.02	5.04	5.05	3.43
	10	8.83	5.13	14.35	6.80	8.36	5.31
	11	8.74	5.23	14.33	6.76	8.15	5.17
	12	8.98	5.10	14.72	6.50	8.58	5.44
	13	8.92	5.34	14.31	6.65	8.40	5.35
	14	8.96	5.21	13.62	7.15	9.13	5.62
	15	15.35	9.23	21.65	12.57	14.81	10.12
	16	14.52	8.33	20.99	11.96	13.72	9.19
	17	15.85	9.82	21.83	14.13	15.13	10.14
	18	16.71	10.30	22.14	14.54	15.36	10.48
	19	16.06	9.88	20.93	13.92	14.98	9.84
	20	8.55	5.30	12.88	8.12	9.12	5.97
	21	9.06	5.62	12.73	8.19	9.21	6.01
	22	8.17	5.24	12.46	8.26	8.99	5.81
Corrugator 2	1	5.32	3.01	8.56	4.39	4.83	2.93
	2	4.88	2.63	8.40	4.27	4.98	3.05
	3	4.64	2.70	6.71	3.47	3.70	2.32
	4	4.92	2.72	8.20	4.12	4.95	2.98
	5	8.78	4.89	13.22	6.33	9.27	5.15
	6	8.60	4.84	13.10	6.06	8.90	4.92
	7	4.80	2.83	8.22	4.12	5.00	2.98
	8	8.58	4.59	12.93	5.95	9.07	5.06
	9	8.88	4.79	13.38	6.45	9.43	5.27
	10	8.74	4.66	13.42	6.34	9.51	5.20
	11	13.82	8.76	19.59	12.45	12.52	9.08
	12	12.52	7.92	16.06	10.82	9.57	6.90
	13	12.21	7.40	16.86	10.63	9.93	7.09
	14	6.72	3.94	9.59	5.55	5.03	3.45
	15	8.04	5.04	11.61	7.07	7.83	5.29
	16	12.04	7.30	16.37	10.46	9.62	6.86
	17	7.38	4.59	10.82	6.50	6.82	4.47
	18	7.40	4.40	10.93	6.98	6.68	4.68
	19	7.93	4.87	12.11	7.19	7.92	5.28
Corrugator 3	1	5.60	4.06	8.01	4.88	5.24	3.37
	2	6.06	3.60	8.28	4.68	5.18	3.21
	3	12.06	7.25	17.45	10.24	10.91	7.16
	4	11.34	7.06	17.26	10.11	10.92	7.16
	5	10.14	6.49	14.43	8.43	9.23	5.72
	6	10.39	5.95	14.91	8.47	9.01	5.90
	7	14.85	9.73	22.22	14.23	15.82	11.15
	8	15.03	9.79	20.30	12.34	14.00	9.54
	9	15.25	9.73	21.08	12.77	14.41	10.27
	10	4.70	2.90	8.16	4.79	4.50	2.96
	11	4.75	2.91	8.16	4.56	4.50	2.93
	12	6.20	3.78	10.17	5.77	6.48	4.06
	13	5.73	3.64	9.07	5.14	5.52	3.50
	14	6.31	4.13	10.33	6.27	6.92	4.62
	15	5.11	3.20	8.22	5.19	4.75	3.38

Appendix 6

Table A7. Paper and corrugated board compression strength reduction after exposure to high relative humidity conditions.

	Sample	Board Measured			Liner 1						Fluting 1						Liner 2						Fluting 2						Liner 3					
		ECT_1	ECT_2	ΔECT	SCT_1	SCT_2	ΔSCT	RCT_1	RCT_2	ΔRCT	SCT_1	SCT_2	ΔSCT	RCT_1	RCT_2	ΔRCT	SCT_1	SCT_2	ΔSCT	RCT_1	RCT_2	ΔRCT	SCT_1	SCT_2	ΔSCT	RCT_1	RCT_2	ΔRCT	SCT_1	SCT_2	ΔSCT	RCT_1	RCT_2	ΔRCT
		kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%	kN/m		%
Corrugator 1	1	14.40	8.37	41.9%	3.696	1.880	49.1%	2.64	1.54	41.7%	3.360	2.000	40.5%	1.98	1.33	32.8%	3.777	1.929	48.9%	2.69	1.58	41.3%	3.263	1.904	41.6%	1.98	1.25	36.9%	3.796	2.024	46.7%	2.61	1.52	41.8%
	2	21.30	12.94	39.2%	8.642	5.045	41.6%	6.40	4.32	32.5%	3.496	2.225	36.4%	2.45	1.62	33.9%	8.189	4.903	40.1%	5.76	3.90	32.3%	3.666	2.331	36.4%	2.42	1.66	31.4%	8.373	5.042	39.8%	6.36	4.29	32.5%
	3	15.00	9.04	39.7%	3.897	2.429	37.7%	2.78	1.84	33.8%	3.200	1.987	37.9%	2.31	1.55	32.9%	4.040	2.359	41.6%	2.65	1.65	37.7%	3.568	2.196	38.5%	2.49	1.7	31.7%	4.059	2.270	44.1%	2.88	1.80	37.5%
	4	15.28	9.13	40.2%	3.828	2.198	42.6%	2.64	1.72	34.8%	3.412	2.190	35.8%	2.27	1.62	28.6%	3.978	2.371	40.4%	2.92	1.79	38.7%	3.613	2.238	38.1%	2.38	1.59	33.2%	4.086	2.373	41.9%	2.73	1.76	35.5%
	5	11.87	7.74	34.8%	2.555	1.444	43.5%	1.67	1.10	34.0%	2.522	1.578	37.4%	1.48	1.04	29.7%	2.392	1.358	43.2%	1.53	1.01	34.0%	2.430	1.620	33.3%	1.46	1.05	28.1%	4.699	2.736	41.8%	3.32	2.21	33.4%
	6	5.17	3.56	31.1%	2.662	1.460	45.2%	1.63	1.08	33.7%	2.769	1.674	39.5%	1.50	1.16	22.7%	2.562	1.439	43.8%	1.72	1.12	34.9%												
	7	6.06	3.93	35.1%	2.711	1.490	45.0%	1.69	1.11	34.3%	2.800	1.695	39.5%	1.55	1.19	23.2%	2.572	1.449	43.7%	1.78	1.17	34.3%												
	8	5.65	3.74	33.8%	2.528	1.421	43.8%	1.54	0.92	40.3%	2.984	1.891	36.6%	1.73	1.17	32.4%	2.468	1.436	41.8%	1.71	1.07	37.4%												
	9	5.61	3.57	36.4%	2.463	1.432	41.9%	1.70	1.05	38.2%	2.439	1.717	29.6%	1.34	1.03	23.1%	2.362	1.355	42.6%	1.59	1.03	35.2%												
	10	8.83	5.13	41.9%	4.691	1.959	58.2%	2.78	1.61	42.1%	3.898	1.975	49.3%	2.05	1.40	31.7%	4.554	2.257	50.4%	2.89	1.87	35.3%												
	11	8.74	5.23	40.2%	4.685	1.943	58.5%	2.73	1.60	41.4%	3.890	1.967	49.4%	2.00	1.35	32.5%	4.545	2.240	50.7%	2.80	1.80	35.7%												
	12	8.98	5.10	43.2%	5.226	2.153	58.8%	2.98	1.66	44.3%	3.699	1.643	55.6%	2.03	1.44	29.1%	4.647	2.195	52.8%	2.94	1.89	35.7%												
	13	8.92	5.34	40.1%	4.807	2.166	54.9%	2.78	1.72	38.1%	3.711	1.754	52.7%	2.06	1.37	33.5%	4.643	2.190	52.8%	2.92	1.84	37.0%												
	14	8.96	5.21	41.9%	4.784	2.588	45.9%	3.63	2.09	42.4%	3.200	1.812	43.4%	1.96	1.27	35.2%	4.644	2.192	52.8%	2.93	1.87	36.2%												
	15	15.35	9.23	39.9%	3.846	2.108	45.2%	2.60	1.74	33.1%	3.546	2.338	34.1%	2.51	1.84	26.7%	4.213	2.427	42.4%	2.87	1.88	34.5%	3.450	1.952	43.4%	2.29	1.62	29.3%	4.0725	2.180	46.5%	2.805	1.78	36.5%
	16	14.52	8.33	42.6%	3.687	2.210	40.1%	2.45	1.68	31.4%	3.361	1.966	41.5%	2.30	1.61	30.0%	3.984	2.250	43.5%	2.52	1.67	33.7%	3.597	2.052	43.0%	2.36	1.56	33.9%	3.864	2.038	47.3%	2.42	1.53	36.8%
	17	15.85	9.82	38.0%	3.946	2.491	36.9%	2.76	1.82	34.1%	3.733	2.642	29.2%	2.65	1.83	30.9%	3.904	2.344	40.0%	2.55	1.67	34.5%	3.721	2.481	33.3%	2.59	1.83	29.3%	3.839	2.322	39.5%	2.69	1.67	37.9%
	18	16.71	10.30	38.4%	3.972	2.519	36.6%	2.73	1.86	31.9%	3.733	2.642	29.2%	2.65	1.83	30.9%	4.014	2.525	37.1%	2.75	1.82	33.8%	3.721	2.481	33.3%	2.59	1.83	29.3%	4.014	2.525	37.1%	2.75	1.82	33.8%
	19	16.06	9.88	38.5%	3.888	2.439	37.3%	2.83	1.82	35.7%	3.492	2.454	29.7%	2.41	1.68	30.3%	3.750	2.459	34.4%	2.69	1.69	37.2%	3.375	2.366	29.9%	2.38	1.56	34.5%	3.952	2.466	37.6%	2.94	1.92	34.7%
	20	8.55	5.30	38.0%	3.939	2.334	40.7%	2.76	1.77	35.9%	3.665	2.509	31.5%	2.64	1.76	33.3%	3.770	2.251	40.3%	2.64	1.72	34.8%												
	21	9.06	5.62	38.0%	3.623	2.180	39.8%	2.72	1.68	38.2%	3.665	2.509	31.5%	2.64	1.76	33.3%	3.944	2.473	37.3%	2.77	1.85	33.2%												
	22	8.17	5.24	35.9%	3.952	2.466	37.6%	2.94	1.92	34.7%	3.375	2.366	29.9%	2.38	1.56	34.5%	3.750	2.459	34.4%	2.69	1.69	37.2%												
Corrugator 2	1	5.32	3.01	43.4%	2.933	1.477	49.6%	1.63	0.99	39.3%	2.438	1.240	49.1%	1.30	0.81	37.7%	2.380	1.261	47.0%	1.47	0.86	41.5%												
	2	4.88	2.63	46.1%	2.907	1.427	50.9%	1.71	1.00	41.5%	2.224	1.214	45.4%	1.23	0.79	35.8%	2.539	1.226	51.7%	1.63	1.00	38.7%												
	3	4.64	2.70	41.8%	2.634	1.275	51.6%	1.62	1.02	37.0%	1.716	0.893	48.0%	0.84	0.52	38.1%	1.791	1.006	43.8%	0.96	0.61	36.5%												
	4	4.92	2.72	44.7%	2.571	1.314	48.9%	1.69	1.02	39.6%	2.401	1.185	50.6%	1.33	0.81	39.1%	2.436	1.233	49.4%	1.49	0.88	40.9%												
	5	8.78	4.89	44.3%	3.663	1.780	51.4%	2.68	1.40	47.8%	3.096	1.503	51.5%	1.99	1.12	43.7%	5.436	2.551	53.1%	3.94	2.26	42.6%												
	6	8.60	4.84	43.7%	3.915	1.881	52.0%	2.80	1.46	47.9%	3.159	1.506	52.3%	1.98	1.12	43.4%	4.982	2.176	56.3%	3.47	1.97	43.2%												
	7	4.80	2.83	41.0%	2.595	1.314	49.4%	1.74	1.02	41.4%	2.401	1.185	50.6%	1.33	0.81	39.1%	2.436	1.233	49.4%	1.49	0.88	40.9%												
	8	8.58	4.59	46.5%	3.861	1.893	51.0%	2.88	1.51	47.6%	3.118	1.493	52.1%	2.03	1.20	40.9%	4.921	2.074	57.9%	3.49	1.95	44.1%												
	9	8.88	4.79	46.1%	3.861	1.893	51.0%	2.88	1.51	47.6%	3.118	1.493	52.1%	2.03	1.20	40.9%	5.370	2.568	52.2%	3.85	2.16	43.9%												
	10	8.74	4.66	46.7%	4.193	1.877	55.2%	2.93	1.46	50.2%	3.145	1.594	49.3%	1.98	1.15	41.9%	5.041	2.341	53.6%	3.95	2.21	44.1%												
	11	13.82	8.76	36.6%	3.786	2.173	42.6%	2.81	1.82	35.2%	2.998	1.967	34.4%	1.59	1.21	23.9%	4.283	2.692	37.1%	2.91	2.19	24.7%	2.698	1.901	29.5%	1.41	1.12	20.6%	3.615	2.225	38.5%	2.64	1.84	30.3%
	12	12.52	7.92	36.7%	3.070	1.773	42.2%	1.77	1.10	37.9%	2.413	1.434	40.6%	1.27	0.91	28.3%	2.821	2.116	25.0%	1.86	1.41	24.2%	2.485	1.799	27.6%	1.47	1.08	26.5%	3.387	2.472	27.0%	2.16	1.64	24.1%
	13	12.21	7.40	39.4%	3.070	1.773	42.2%	1.77	1.10	37.9%	2.413	1.434	40.6%	1.27	0.91	28.3%	3.109	2.133	31.4%	1.94	1.47	24.2%	3.109	2.039	34.4%	1.94	1.42	26.8%	3.074	1.943	36.8%	1.81	1.32	27.1%
	14	6.72	3.94	41.4%	3.139	1.727	45.0%	1.62	1.10	32.1%	2.706	1.420	47.5%	1.33	0.87	34.6%	2.850	1.933	32.2%	1.64	1.19	27.4%												
	15	8.04	5.04	37.3%	4.053	2.458	39.4%	2.90	2.01	30.7%	2.455	1.493	39.2%	1.32	0.93	29.5%	4.021	2.461	38.8%	3.03	1.94	36.0%												
	16	12.04	7.30	39.4%	3.070	1.773	42.2%	1.77	1.10	37.9%	2.413	1.434	40.6%	1.27	0.91	28.3%	3.109	2.133	31.4%	1.94	1.47	24.2%	3.109	2.039	34.4%	1.94	1.42	26.8%	2.850	1.933	32.2%	1.64	1.19	27.4%
	17	7.38	4.59	37.8%	3.007	1.751	41.8%	1.87	1.13	39.6%	2.446	1.450	40.7%	1.32	0.89	32.6%	4.288	2.656	38.1%	3.05	2.06	32.5%												
	18	7.40	4.40	40.5%	3.007	1.751	41.8%	1.87	1.13	39.6%	2.744	1.893	31.0%	1.55	1.15	25.8%	3.969	2.505	36.9%	2.58	1.89	26.7%												
	19	7.93	4.87	38.6%	4.288	2.485	42.0%	3.05	1.93	36.7%	2.460	1.525	38.0%	1.30	0.92	29.2%	4.277	2.507	41.4%	3.00	2.03	32.3%												
Corrugator 3	1	5.60	4.06	27.6%	2.701	1.653	38.8%	1.86	1.22	34.4%	2.049	1.208	41.0%	1.16	0.76	34.5%	2.684	1.676	37.6%	1.90	1.18	37.9%												
	2	6.06	3.60	40.6%	2.768	1.520	45.1%	1.74	1.12	35.6%	2.073	1.158	44.1%	1.20	0.71	40.8%	2.862	1.679	41.3%	1.90	1.18	37.9%												
	3	12.06	7.25	39.9%	3.220	1.872	41.9%	1.75	1.20	31.4%	2.890	1.690	41.5%	1.97	1.22	38.1%	3.265	2.025	38.0%	1.95	1.38	29.2%	3.228	1.788	44.6%	2.14	1.33	37.9%	2.763	1.676	39.3%	1.69	1.16	31.4%
	4	11.34	7.06	37.8%	3.029	1.735	42.7%	1.76	1.20	31.8%	2.890	1.690	41.5%	1.97	1.22	38.1%	3.265	2.025	38.0%	1.95	1.38	29.2%	3.228	1.788	44.6%	2.14	1.33	37.9%	2.763	1.676	39.3%	1.69	1.16	31.4%
	5	10.14	6.49	36.1%	2.832	1.707	39.7%	1.94	1.20	38.1%	2.167	1.278	41.0%	1.29	0.81	37.2%	2.822	1.568	44.4%	1.85	1.15	37.8%	2.217	1.341	39.5%	1.38	0.85	38.4%	2.878	1.634	43.2%	1.85	1.14	38.4%
	6	10.39	5.95	42.7%	3.151	1.843	41.5%	1.76	1.33	24.4%	2.167	1.278	41.0%	1.29	0.81	37.2%	2.822	1.568	44.4%	1.85	1.15	37.8%	2.465	1.303	47.1%	1.36	0.85	37.5%	2.731	1.589	41.8%	1.84	1.19	35.3%
	7	14.85	9.73	34.4%	4.965	3.149	36.6%	3.64	2.52	30.8%	3.127	1.938	38.0%	1.94	1.37	29.4%	4.371	2.832	35.2%	3.35	2.42	27.8%	3.270	2.028	38.0%	2.09	1.43	31.6%	4.293	2.921	32.0%	3.42	2.45	28.4%
	8	15.03	9.79	34.9%	3.757	2.000	46.8%	2.57	1.59	38.1%	2.759	1.584	42.6%	1.68	1.10	34.5%	4.793	3.160	34.1%	3.51	2.57	26.8%	2.937	1.685	42.6%	1.829	1.16	36.6%	4.572	3.062	33.0%	3.49	2.53	27.5%
	9	15.25	9.73	36.2%	3.450	1.833	46.9%	2.47	1.59	35.6%	3.135	1.906	39.2%	1.94	1.41	27.3%	4.836	2.949	39.0%	3.47	2.64	23.9%	3.300	1.966	40.4%	1.98	1.35	31.8%	4.684	3.111	33.6%	3.53	2.56	27.5%
	10	4.70	2.90	38.3%	2.702	1.521	43.7%	1.50	1.03	31.3%	2.034	1.271	37.5%	1.07	0.69	35.5%	2.592	1.480	42.9%	1.49	0.96	35.6%												
	11	4.75	2.91	38.7%	2.544	1.489	41.5%	1.53	0.97	36.6%	2.078	1.180	43.2%	1.06	0.69	34.9%	2.683	1.404	47.7%	1.48	0.99	33.1%												
	12	6.20	3.78	39.0%	2.947	1.628	44.8%	1.83	1.18	35.5%	2.945	1.708	42.0%	1.94	1.17	39.7%	3.066	1.736	43.4%	1.91	1.23	35.6%												
	13	5.73	3.64	36.5%	2.754	1.486	46.0%	1.87	1.16	38.0%	2.390	1.467	38.6%	1.19	0.86	27.7%	2.945	1.589	46.0%	1.97	1.13	42.6%												
	14	6.31	4.13	34.5%	3.752	2.092	44.2%	2.71	1.68	38.0%	2.250	1.479	34.3%	1.23	0.91	26.0%	3.700	2.287	38.2%	2.64	1.78	32.6%												
	15	5.11	3.20	37.4%	2.674	1.636	38.8%	1.53	1.10	28.1%	2.250	1.479	34.3%	1.23	0.91	26.0%	2.667	1.661	37.7%	1.65	1.12	32.1%												
Average strength reduction				**39.2%**			**44.8%**			**37.2%**			**41.0%**			**32.8%**			**42.7%**			**34.9%**			**37.8%**			**31.9%**			**39.0%**			**32.8%**