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THE EFFECT OF CYCLIC ENVIRONMENTS ON THE COMPRESSION STRENGTH OF BOXES MADE FROM HIGH-PERFORMANCE (FIBER-EFFICIENT) CORRUGATED FIBERBOARDS

By

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ABSTRACT

THE EFFECT OF CYCLIC ENVIRONMENTS ON THE COMPRESSION STRENGTH OF BOXES MADE FROM HIGH-PERFORMANCE (FIBER-EFFICIENT) CORRUGATED FIBERBOARDS

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The compression strength of boxes made from high-performance (fiber-efficient) linerboards subjected to cyclic environments was investigated. The compression strength of two types of boxes made from fiber-efficient linerboards (regular fiber-efficient linerboards and highly fiber-efficient linerboards) was compared with the compression strength of boxes made from standard linerboards, after exposure to cyclic conditions. The effect of moisture absorption by box materials on compression strength was also investigated.

Exposure to the cyclic conditions used in this study caused significant reduction in compression strength of all box types. Boxes made from regular fiber-efficient linerboards experienced greater loss of strength than boxes made from standard linerboards, after exposure to the cyclic conditions, however, there was no significant difference in their final compression strength. Only marginally significant differences in loss of strength were found for boxes made from highly fiber-efficient linerboards and boxes made from standard linerboards, in addition, no significant difference in their final compression strength was found. Differences in moisture absorption among the box materials was a factor causing the variation in loss of strength among the box types. Compression strength decreased as the moisture content of the box material increased.

Dedicated to

บุญเสริม และ อารยา บุญญะศานต์

(my parents, Boonserm and Araya Boonyasarn)

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INTRODUCTION

Many warehouses are forced to stack containers as high as possible because of their limited storage space. The compression strength of corrugated fiberboard containers made from conventional materials may be inadequate to provide the level of strength required. End-users may need containers that provide greater compression strength at a cost-efficient price.

A conventional way to increase compression strength is to increase the number of fibers in the linerboard and/or medium, or by using a multiwall construction. Although higher levels of compression strength may be obtained, the increased cost may make the container unaffordable. High-performance or fiber-efficient corrugated materials have been developed in an attempt to acquire the needed level of compression strength at an efficient price.

Several technologies are used in the production of high-performance corrugated materials. The technologies that are commonly used in the industry are classified into four categories: chemical enhancement, improvement of fiber orientation, high-pressure forming and multiple medium (Spanlding, 1989). Each of these processes can provide the additional structural strength, and the different methods can be combined to produce one container.

One of the most commonly used techniques is chemical enhancement. In this process, chemicals are impregnated into fibers to create bridging bonds between fibers. The bridging bond welds the fibers together and results in greater resistance to deformation under stressed conditions.

Improvement of fiber orientation redirects the fibers during paper production. Typically most fibers run parallel to the machine direction. Thus the fibers lay horizontally around the box after the container is form. This results in low top-to-bottom compression strength of the final box. If more of the fibers are forced to run perpendicular to the machine direction, the final box will have more fibers running vertically up and down its which results in the higher box compression strength.

High-pressure board forming is a process that uses elevated mechanical pressure to compress paper fibers during the manufacturing process. This creates better fiber-to-fiber bonding and a denser sheet, and as a result there is an increase in the material's strength. High-pressure forming also tends to squeeze more water out of the pulp. This causes a decrease in material moisture content and thus better strength.

Multiple medium is a technique that obtains better compression strength by laminating two or more layers of medium together. This can create a single-wall board which performs as well as double-wall boards weighing up to 10 percent or more.

However, despite these approaches, there is concern that high-performance boxes may not perform as well as conventional boxes when subjected to cyclic environments. A "cyclic environment" is defined here as one where the climatical conditions of temperature and relative humidity fluctuate through several levels. Simulation of real-life situations using cyclic environments are used because most warehouses are often unable to control the effect of rapidly changing weather conditions even with climate control systems. In addition, containers that are shipped regionally, nationally or internationally may be sent from areas of low humidity conditions to high humidity environments and vice versa.

Cyclic environments have been shown to have an adverse effect on paper's performance under loads (Byrd, 1988). Cyclic changes in relative humidity results in a more rapid decrease of compression strength in corrugated fiberboards than a constant relative humidity condition. Thus, loaded boxes exposed to cyclic relative humidity conditions are most likely to fail before similarly loaded boxes subjected to a constant relative humidity environment. A box that performs acceptably in a constant relative humidity condition might not be acceptable in a cyclic environment.

There have been extensive studies conducted to examine the performance of various kinds of fiberboards under cyclic conditions. These range from corrugated fiberboards made from high-yield, normal-yield, virgin and recycled pulps to corrugated fiberboards made with press-dried and conventionally-dried linerboard. Yet, the effect of cyclic environments on corrugated boxes made from high-performance materials has not been reported.

Compression strength is most widely used as a measure of final box performance because of its relationship to box stacking performance. It also can be used as an indicator of the overall quality of the materials and the efficiency of the box manufacturing process.

The objectives of this study are:

- To measure and compare the compression strength of corrugated boxes made from two types of high-performance linerboards, subjected to cyclic and non-cyclic environments.
- To compare the compression strength of corrugated boxes made from high-performance linerboards in a cyclic environment to that of corrugated boxes made from conventional linerboards in the same cyclic environments.
- To determine the relationship between moisture content and compression strength in high-performance corrugated fiberboard.

LITERATURE REVIEW

I. STANDARD (CONVENTIONAL) CORRUGATED BOX

A corrugated fiberboard box consists of two structural components: corrugating medium and linerboard. The corrugating medium is the fluted or corrugated center of the board, and the linerboard is the flat material attached to the medium.

Corrugating Medium

The corrugating medium is mostly manufactured from semichemical processed hardwood (Kline, 1982). Hardwood fibers are preferred over softwoods because the hardwoods cost less and contribute to the particular type of strength needed in corrugating medium. In the semichemical process, the pulp is not washed thoroughly as with chemical pulp, therefore, lignin and other hemicelluloses are left with the fibers. These chemicals help to bond the web of paper together and form the rigid fluted shape needed. The short hardwood fibers are less flexible than softwoods and, thus, provide stiffness to the corrugating medium. Secondary (recycled) fibers are also used in the corrugating medium, however, they cannot be used for more than 40% of the weight of the paper, otherwise the stiffness will suffer. Fillers and sizing agents are not needed for the medium unless wet strength agents are used to provide water resistance.

Linerboard

Most of the linerboard used for corrugated board is unbleached kraft. The kraft pulping process is basically an alkaline cook. The predominant raw material used to manufacture linerboard is softwood fibers, though the linerboard may contain up to 20% hardwoods or secondary fibers (Kline, 1982). Softwood fibers are required to provide the necessary strength to the linerboard. Mineral fillers are not normally used since they can reduce the strength of the board, however, because of higher fiber costs, clay may be used in order to add to the weight of the board and thus reduce the cost as long as the strength is not reduced too severely. Chemicals may be used to provide water resistance or increase wet strength of the board.

II. HIGH-PERFORMANCE (FIBER-EFFICIENT) CORRUGATED BOX

In recent years, there have been many research studies designed to improve corrugated box performance by improving the compression strength of boxes. Increasing fiber costs, expensive warehouse and truck space, and high quality standards are factors that contribute to this research effort. The development of a process and/or material change which would allow manufacturers to reduce raw material and operational costs without a consequent reduction in paper properties would be enormously significant.

The development of high-performance or fiber-efficient corrugated materials and containers have been extensively introduced to fulfil this need. High-performance corrugated fiberboard is a product that provides substantially more compression strength than the conventional corrugated fiberboard (Talsma, 1989). Several technologies are being used in the production of high-performance corrugated board. Processes as simple as laminating linerboards and mediums together or as complicated as to require special mill process in the papermaking machines are being used. Some use more medium in their boxes than in conventional ones. Several of these techniques improve the linerboard since it is a key attribute which provides compression strength to the corrugated container (Peterson and Fox, 1980). Each process adds a certain amount of strength, different methods can be combined in one container.

Spanlding (1989) classified commonly used processes for the production of high-performance corrugated board into four categories: chemical enhancement, improvement of fiber orientation, high pressure forming, and multiple mediums.

Chemical Enhancement

One of the most commonly used processes to increase compression strength of corrugated board is chemical enhancement (Walthy, 1987). In this process, chemicals are impregnated into wood fibers which can create bridging bonds between the fibers. The bridging welds the fibers together and results in greater resistance to deformation under stressed conditions.

Walthy (1987) reported that the two primary chemicals that are used to create a high compressive strength board are sodium silicate and urea formaldehyde. Both can improve compression strength of boxes made with typical adhesives and processing techniques without sacrifying printability, gluability, or runnability. In addition, both chemicals improve box compression properties in a high humidity conditions.

Urea formaldehyde treated board maintains better strength characteristics after prolonged exposure to high humidity than sodium silicate treated board. However, urea formaldehyde contains low levels of free formaldehyde, which is a probable known carcinogen. This can cause a potential health hazard. Sodium silicate, on the other hand, is less expensive and has almost no negative environmental impact.

Walthy (1987) found that an approximately 10% addition of sodium silicate gave a 42-lb basis weight linerboard the same compressive strength as that of a 69-lb linerboard. As a result, a 69-lb / 26-lb / 69-lb board can be replaced by a treated 42-lb / 26-lb / treated 42-lb board which results in substantial economic saving.

Improvement of Fiber Orientation

Improvement of fiber orientation or fiber cross-linking redirects the fibers during the paper manufacturing process. Typically, fibers runs parallel to the machine direction, thus the fibers lay horizontally around the box after the container is formed. This is the worst direction to obtain high top-to-bottom box compression strength.

Cross linking is a technique that forces more of the fibers to run 90 degree to the machine direction. It reduces the ratio of machine direction (MD) to cross direction (CD). This causes more fibers to run vertically up and down the panels of a container and, as a result, higher compression strength is obtained.

The effect of the fiber orientation was studied by Whitsitt (1988). It was concluded that by reducing the ratio of MD:CD of the linerboard, the CD compression strength of the linerboards was increased and hence, box compression strength.

High-pressure Forming

High-pressure board forming is another commonly-used process to increase compression strength of linerboard. It is performed during paper production. Spanlding (1989) explained that, this technique involves increasing the degree of pressure on the paper fibers to more tightly compress them. This creates better fiber-to-fiber bonding and a denser sheet, the denser the paper the stronger it becomes. As a result, box compression strength is increased. High-pressure forming also tends to squeeze more water out of the pulp. This results in a decrease moisture content of the paper and thus better strength. In addition, Talsma (1989) added that tightly compressed board provides a smoother surface as a barrier against abrasion during handling in the distribution. The consistent porosity of the board also helps assure smoother handling with vacuum-fed packaging equipment.

The influence of high-pressure forming on compression strength was studied by Whitsitt (1988). He found that the highly pressed linerboard gained more compression strength and combined boards made with these linerboards exhibited improved edge crush values.

Multiple Medium

The lamination of two or more layers of medium together is another innovation that offers increased compression strength (Spanlding, 1989) Two or more layers of medium are laminated together combining them with linerboard into a corrugated board. The glue can be a simple starch based adhesive. Spanlding stated that double medium corrugated boxes retain a thin, single-wall construction, but they can perform as well as double-wall boxes weighting up to 10 percent more.

III. COMPRESSION STRENGTH

The performance requirements of a corrugated shipping container range from need for advertising appeal to mechanical strength to protect the product. In transportation and storage of goods, sufficient strength is required to sustain the load of several filled boxes placed on top, and to protect contents from forces resulting from freight cars humping, from end thrust in a truck that stops suddenly, or from forces caused by rough handling (Kellicutt, 1960). Kolseth and Ruvo (1983) added that in many cases, additional strength is required to resist vibrational load during the shipment.

Compression strength is generally considered to be the most prominent indicator of final box performance. There are two reasons for this (McKee, 1961): (1) compression strength is directly related to warehouse stacking performance and (2) laboratory tests of box compression strength is a useful tool to evaluate the overall quality of the materials and the quality of its manufacture.

In order to successfully design corrugated boxes for long-term storage, package designers have to know how much strength containers must have (Koning and Stern, 1977). Quite often, this has been decided based on design curves of compressive strength and stacking time period, past experience, trial and error, or guesswork. For instance, Kellicutt and Landt (1951) developed design curves by conducting compression tests to find a relationship between box compressive strength and the length of time that containers were exposed to dead loads at a specific temperature and humidity. Their design curve shows that, in general, for dead loads less than 75% of the box compressive strength, each decrease of 8 percentage points in the ratio of the dead load to the compressive strength resulted in extension of failure time by about eight times.

Before selecting materials and designing box structure to acquire the necessary box compressive strength, it is important to examine how a compressive load is distributed on corrugated boxes. McKee, et al (1961) described the top-to-bottom compression behavior of most conventional, vertical flute, corrugated boxes in tests as follows:

> "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. The beginning of bowing of the panels may or may not be markedly evident , depending on whether the panel is initially nearly flat or, on the other hand, is warped or bowed due to box manufacture and setup. Having become unstable, the central region of each panel suffers an appreciable decrease in its ability to accept further increase in load.
>
> Bowing of the panels, however, does not usually coincide with the maximum load-carrying capacity of the box. The combined board near the vertical edges of each panel is constrained to remain essentially flat because the adjacent panels of the end thrust is capable of accepting substantially greater load (by reason of its stable configuration) than the most centrally located regions of the panel."

McKee, et al (1961) added that the centermost portions of the panels carry only one-half to two-thirds the intensity of load sustained at the edges of the box failure. The box reaches its maximum load when the combined board at or near a corner of a panel ruptures. Maltenfort (1980) also found that the edges or corners of the box carried 64 percent of the total compressive load and that the panels carried the remaining 36 percent. The load carried by any particular corner did not differ from that carried by any of the other three.

There are several ways to evaluate box compression strength. Compression testing of the empty box has been widely used to measure the compression strength. It is probably the best "all-around" method for evaluating the final box quality (Maltenfort, 1988). Box compression test reflects several factors that contribute to box strength (McKee, 1963). Contributing factors include grade of the combine boards, box dimensions, and quality of the manufacture.

McKee, et al (1963) developed an equation which is known as the McKee formula and is used to predict box compression strength. The formula is as follows.

$$\text{Top-to-Bottom Compression} = 5.87\ P_m \sqrt{Zh}$$

where: P_m = edgewise compression, in lbs / in

Z = box perimeter (2L + 2W), in inches

h = board caliper, in inches

McKee (1963) explained that in box compression, box failure is triggered by failure of the combined board at the vertical edges. Both linerboards and corrugating mediums are approximately uniformly stressed in edgewise compression. Therefore, in the formula, the edgewise compression strength of corrugated board (in the direction of the flutes) is primarily important to predict the box compression strength.

According to McKee, et al (1961), the board at the center region of each panel carries less load than the board near the edges, however, it is significant and must be considered in predicting box strength. The load-carrying capacity of the central region of each panel reflects the bending characteristics of the combined board and the panel dimensions. Therefore, flexural stiffness, the measure of the ability of the board to resist bending, should be included in any analysis of box compression strength. Since determining the stiffness value of corrugated board is very cumbersome, the board thickness, which is well correlated with stiffness, has been introduced to modify the original equation.

Nordman, et al (1978) stated that the thickness of corrugated board has a major influence on the compressive strength of boxes. Thus, it is important to avoid subjecting the board to treatments which lead to a reduction in the thickness of the board. However, during manufacture, board components or combined boards may be damaged by compressive forces. For example, when the board is run through printing or converting machines, perpendicular forces applied to the surface of the board may cause considerable sidewall compression. As a result, the board does not posses the ultimate strength obtainable from its components.

The asymmetrical construction of corrugated board can also influence the distribution of compressive loads on boxes. Asymmetrical construction refers to the corrugated boards that have different weight grades, ie. different stiffness levels on the inside and outside linerboards. In practice all boxes are filled, so that any bulge is outward. That means the outside linerboard will be stressed in tension while the inside will be in compression. Maltenfort (1980) explained that as long as both linerboards have the same weight grades, load distribution does not affect "inside" and "outside" differentially. If the construction is asymmetrical, then a heavier or stiffer linerboard inside the box will accept a higher compression load than if the lighter or less stiff linerboard had been in that position. Therefore, the heavier liner should be located inside in order to acquire the most box compression strength.

There are several other factors that have an influence on the compressive strength of corrugated boxes. These include: moisture content of board, flute construction, misalignment in stacking, content's role in supporting the load and cyclic environments.

IV. COMPRESSION STRENGTH TESTING METHOD

Estimation of box compression strength based on individual component, combined board and box criteria can be used to determine, before the box is manufactured, how much compression strength it will have (Maltenfort, 1988). The need for such procedures has increased since more corrugated boxes are being used as the shipping containers. There are a number of methods which can be used to evaluate and predict compression strength of corrugated boxes.

Box Compression Test

According to Maltenfort (1988), the box compression test is considered to be the best "all-around" method for predicting the final box performance. McKee et al (1961) stated that the box compression test, however, has a critical limitation. The limitation is that the box compression test generally cannot distinguish between several factors which contribute to box strength. These factors are: (1) quality of the basic materials - linerboard and corrugating medium, (2) box dimensions, (3) corrugating and conversion variables, and (4) environmental effects (humidity, duration of loads, etc.). In the event of inadequate box strength, it may not be apparent whether the fault is due to the linerboards or corrugating mediums, or the manufacturing process, or the conversion operation.

In a compression test for shipping containers, according to ASTM D642-76, a box is placed on the lower platen of a compression tester which is connected either to a load cell or to a mechanical scale. The upper platen is lowered onto the box at a constant rate of 0.5 inch per minute until the box collapses. A load-deflection curve is recorded as the test proceeds (see Figure 1).

Edge Crush Test

Stott (1988) believes that the edge crush or edgewise compression test (ECT) is the best measurement of board properties. Among the different board properties, the ECT value has the closest relationship with final box performance. Moreover, it is the most important input into the McKee formula, which is the most used equation for prediction of box compression strength. McKee et al (1961) stated that the edgewise compression strength of the corrugated board is a major factor in the top-load compression strength of a box because in testing, it has the same type of failure which triggers box failure in top-load compression.

In the ECT test, a rectangular specimen of combined board is placed on its edge in a compression tester. The load is applied perpendicular to the flutes. The largest force that the specimen can withstand without failure is reported as the edge crush value.

There are several ECT methods being used in laboratories (Stott, 1988). These methods include TAPPI, ASTM, FEFCO Method No.8, JIS 0402, FPL proposal, IPC proposal and the Weyerhaeuser method. Stott reported that the TAPPI method widely used in the United States is not well suited to routine use due to the complications and delays resulting from the required edge-waxing step. European Federation of Corrugated Board Manufactures (FEFCO) recommended adopting FEFCO method No.8 as the international standard method. One of the reasons is that this method is operationally convenient with a known and acceptable level of interlaboratory agreement. Moreover, its

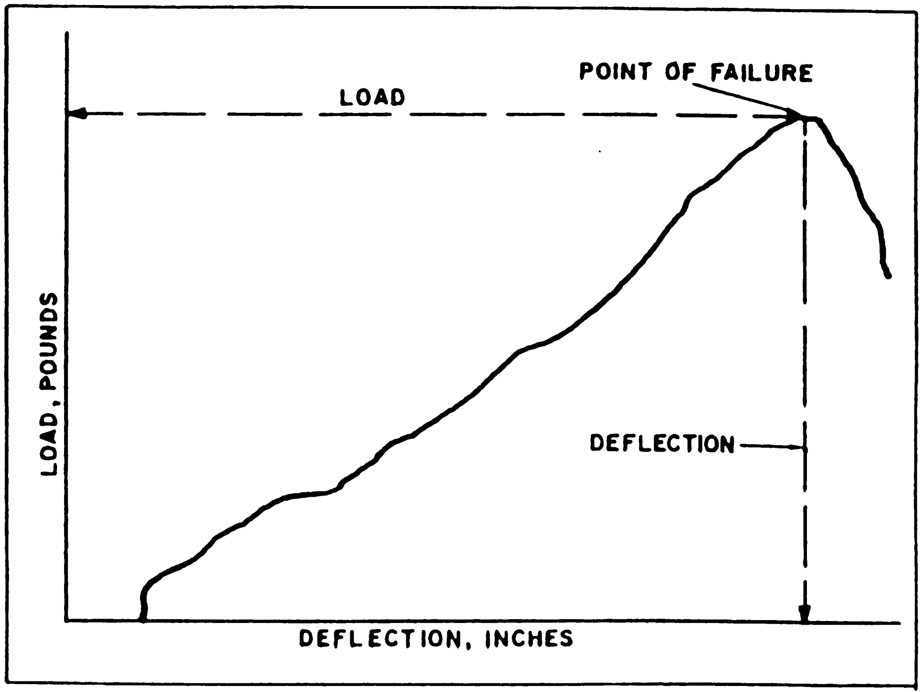


Figure 1 Load-deflection curve from compression test.

results correlate highly with results of other test methods that use more elaborate and expensive methods. In FEFCO Method No.8, a Billerud cutter, which simultaneously cuts both loading edges of the sample in a clear and precise manner, is required.

Flexural Stiffness

McKee, et al (1962) stated that the top-load compression strength of corrugated boxes depends mainly on the edgewise compression strength of the corrugated board in the cross-machine direction, and to a considerable extent on the flexural stiffness in both machine and cross direction of the corrugated board. Flexural stiffness is the ability of the board to resist bending.

McKee, et al (1961) explained that side and end panels of a vertical flute, RSC box usually bow outward or inward when subjected to top-to-bottom compression. Bending of the panels limits their load-carrying ability over the central region of each panel. As a result, analysis of box compression strength essentially includes consideration of the flexural stiffness of corrugated board.

One of the most commonly used methods to measure flexural stiffness is the four-point beam test. In this test (TAPPI T 820 cm-85), a specimen cut either in the machine or cross machine direction is placed on two supporting anvils. Two loading anvils are placed on the top of the specimen. The top anvils are then successively loaded with weights of equal increments. The deflection caused by each weight is measured with a micrometer. Flexural stiffness is calculated as follows:

$$D = (1/16)(P/Y)(L^3/w)(a/L)$$

Where, D = flexural stiffness

P = sum of the two weights

Y = sum of the deflection of the two weights

L = distance between the bottom support anvils, cm (in.)

a = distance between the bottom support anvil and upper loading anvil

w = width of the specimen, cm (in.)

V. EFFECT OF TEMPERATURE AND HUMIDITY ON COMPRESSION STRENGTH OF CORRUGATED BOX

The moisture content of paper has an important effect on paper properties (Kline, 1982). Normally paper contains about 5% moisture when it is dry. Since paper is made of cellulose, which is highly hygroscopic, it will absorb water from the atmosphere if the two are not in balance. Generally, variations in moisture content can cause the paper to curl, wrinkle, change dimension or lose strength and can create other handling difficulties.

Kellicutt (1961) stated that the most serious factor limiting the use of corrugated boxes has been the effect of moisture on box compressive strength. As a result, paperboard components are specially treated by adding wet strength agents in order to retain the dry stiffness when the box material is wet. One of the most commonly used wet strength chemical is melamine formaldehyde (MF) (Kline, 1982). The MF will react during the drying of the paper to form a water-resistant compound. By adding the MF to the pulp stock prior to paper web formation, it can adhere to the fibers and also be deposited on the bond areas during web formation. The MF then functions in the paper to protect the bonding and also to help hold the fibers together when the paper is wetted. Therefore, when corrugated boxes are subjected to a damp condition, wet strength agents will retard the absorption of moisture by the highly hygroscopic wood fibers of the fiberboard. This is especially true when treated boxes are subjected to high humidity for short periods of time. However, when the same boxes are subjected to high humidity for prolonged periods of time, water vapor will eventually reach the fibers and cause reduction of box compressive strength. This reduction, on a percentage basis, is generally the same as for the untreated ones. However, MF's advantage is that it protects boxes from the adverse effect of moisture in short time exposure.

Kellicutt (1961) stated that corrugated box material has the most compressive strength when it contains the lowest moisture content. As moisture content increases, there is a corresponding decrease in compressive strength. A relationship between compressive strength and moisture content was developed by Kellicutt (1961) as follows:

$$Y = b^{(10)^{-3.01}x}$$

where, Y = compressive strength of box, in lbs.

b = compressive strength at 0 percent moisture content

x = moisture content

Kellicutt (1961) found that boxes made from different materials reacted in essentially the same way for specific increases in moisture content. The compressive strength of the box at a specific moisture content may be found by relating the box to another for which the compressive strength and moisture content are known. The formula is expressed as follows:

$$P = P_1^{(10)^{3.01} x_1 / (10)^{3.01} x_2}$$

where, P = compressive strength to be determined, in lbs.

P_1 = known compressive strength in lbs.

x_1 = moisture content for box with P1 compressive strength

x_2 = moisture content for which the compressive strength is to be determined

The effect of relative humidity (RH) and temperature on the tensile stress-strain properties of softwood kraft linerboards was studied by Benson (1971). The tensile properties investigated included tensile stress, modulus of elasticity, strain to failure, and tensile energy absorption. Benson stated that the effects of temperature on tensile properties consisted of two factors: (1) At any RH level, change in temperature caused a change in the absolute water vapor available to the paper, a change in the absolute vapor pressure acting on the paper, and a resulting change in the paper equilibrium moisture content (EMC). (2) Temperature change directly affects the behavior of paper that is subjected to an external stress through changes in thermal energy levels. If moisture is present, observed effects of temperature change on paper tensile properties are dependent upon interaction between these two factors. Therefore, instead of using conventional methods of interpretation that relate tensile properties to RH, Benson evaluated the effect of RH in term of the specimen EMC. The advantages for this are: (1) It would eliminate the need to know how specimen EMC is reached, whether on an adsorption or desorption isotherm. (2) It would eliminate the difficulty in maintaining fixed temperature and RH conditions. (3) It would eliminate the problem of determining the calibration accuracy of instruments used to measure RH.

The test results showed that as the EMC increased, the tensile properties decreased and as the temperature increased, the tensile properties increased. Both relationships were essentially linear.

Compression strength of boxes held under frozen conditions was studied by Harte, et al (1985). In the study, boxes were held at -17.8 C and -31.7 C. The compression strength of these boxes were compared to the compression strength of boxes held at 22.8 C and 50% RH. From the result, boxes held at 22.8 C were found to have less compression strength than the ones held at temperatures below 0 C. The increase in compression strength was partially provided by the frozen water (ice) in the board. Stiffening of board fibers during freezing was probably a contributing factor. In addition, it was found that thawing of frozen boxes caused reduction in compression strength, however, boxes regained strength when refrozen. Freezing-thaw cycling did not have substantial effect on compression strength of frozen boxes.

VI. THE EFFECT OF CYCLIC CONDITION ON PAPER PROPERTIES

The effect of cycling -relative-humidities on paper properties has been studied by Byrd (1972). He investigated the compression creep response of paper in a changing relative humidity (RH) environment. Creep is a time-dependent deformation of a material under constant stress. In the study, short-column corrugated fiberboard specimens were subjected to edgewise compressive loads during exposure to both cyclic (90-35%) and constant (90%) RH environment. The results showed that creep rates were much greater for the specimens in a cyclic RH environment than for the ones in a constant environment. The creep strains for cyclically conditioned specimens were higher than for the ones in a constant condition. From the results, Byrd concluded that paperboard products under edgewise compressive loading and cycled between 90 and 35% RH would fail sooner than in constant (90%) RH environment even though the average board moisture content may be lower under cyclic RH conditions.

Byrd and Koning (1978) studied the edgewise compression creep, of corrugated fiberboard made from various materials, in cyclic RH environments. Virgin, recycled, high-yield and roughwood southern pine pulps were selected for this study. In comparing the relationship of creep rates of the various materials in both constant and cyclic RH environments, the constant 90% RH creep rates did not vary substantially for any of the corrugated fiberboard specimens. Conversely, in cyclic RH conditions, significant differences in creep rates between these specimens were found. High-yield pulp had the highest cyclic RH creep rate and thus is expected to have the lowest stacking life. Byrd (1988) explained that the poor performance was probably due to the lack of conformability of the high-yield fibers resulting in lower fiber-to-fiber bonding than with virgin conventional-yield pulps. Roughwood pulp, made by adding bark with the chips during pulping, had higher creep rates than non-bark pulp (about 25%). The creep rates of specimens made from recycled fiber were 7-28% higher than for virgin material. The results revealed that increasing pulp yield , adding bark or recycling is detrimental to cyclic RH creep performance. Each of these factors leads to reduction in interfiber bonding. Improvement in interfiber bonding generally results in improved cyclic RH creep performance and thus improvement in expected box stacking performance.

Setterholm and Benson (1977) found that press-dried, high-yield, hardwood fiberboard specimens performed as well in compression as conventionally dried, normal-yield, softwood fiberboard specimens in cyclic RH environment. The press-drying process provides improvement in moisture resistance and increase in interfiber bonding which results in improved creep performance of high-yield pulps in cyclic environments.

Byrd (1984) compared the creep response of board components (linerboard and corrugating medium) that were compared to the results of his earlier studies on combined board. He found that the combined board creep was 2-5 times faster than board component measurement indicated. He also found that press-dried, high-yield, oak linerboard did not creep as fast as conventionally dried, softwood (virgin) linerboard in a cyclic RH environment. Conventionally dried, low-yield, oak linerboards deformed at a greater rate than either conventionally dried, softwood linerboards or press-dried, low-yield oak linerboards.

Byrd (1984) stated that since different cellulosic materials absorb and desorb moisture at different rates, it is not sufficient to only record ambient RH changes during an experiment. Byrd, thus, investigated actual moisture loss and gain during RH cycling of the board components in order to better understand the causes of creep rate acceleration. The results showed that linerboard made from high-yield pulp sorbed moisture much faster than virgin linerboard did. Sorption rates and lignin content were found to be related: as the lignin content in pulp is increased, the sorption rate rises. The recycled and press-dried linerboards are two exceptions to this phenomenon. Recycling reduces the rate of moisture sorption due to the debonding effects of drying. The press drying process provides paper more moisture resistance which results in less moisture sorption rate and hence less creep rate. Therefore, even though press-dried linerboard has a relatively high lignin content, it creeps and picks up moisture at about the same rate as virgin softwood linerboard.

Byrd (1984) concluded that the increase in creep rate is apparently related to the moisture sorption rate. Therefore, linerboards made from high-yield pulps creep faster and sorb moisture faster than specimens made from virgin, conventional-yield pulps.

VII. DISTRIBUTION ENVIRONMENT

Variations in humidity and temperature can and do occur during transportation, in warehouses, and even in retail stores. In many cases, shipping containers are moved from low-humidity environments to high humidity environments and vice versa.

Considine, et al (1989) stated that despite having control systems and insulation, warehouses are often unable to prevent the cyclic humidity changes caused by rapidly changing weather condition. Temperature and relative humidity fluctuate every day and night. For example, Figure 2 shows wide fluctuations of outdoor relative humidity (RH) for Madison, Wisconsin, between 1-10 February 1987, as measured by the National Weather Service. As a result of the weather fluctuations and the lack of elaborate moisture control systems in the manufacture plant, transportation and storage, most corrugated containers experience moisture sorption during their service lives.

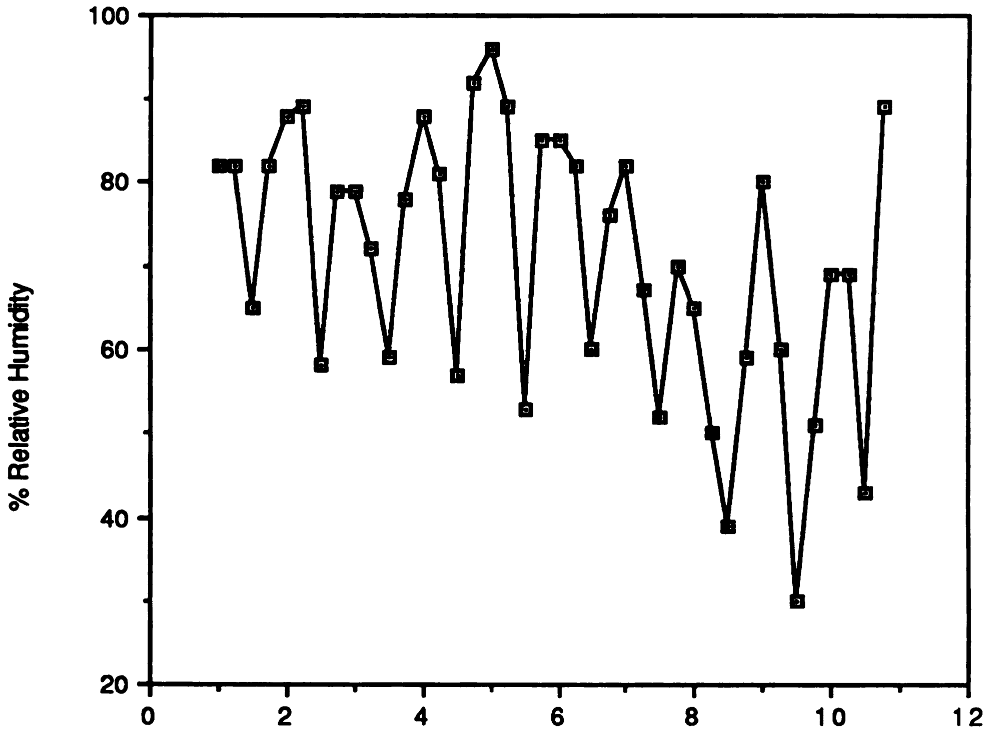


Figure 2 Outdoor relative humidity for Madison, 1-10 February, 1987

EXPERIMENTAL PROCEDURES

TEST MATERIALS

The fiberboard materials and corrugated fiberboard boxes used in this study were suppplied by a commercial manufacturer of corrugated packaging. Description of the fiberboard materials and corrugated fiberboard boxes is as follows:

1. Boxes made from two types of standard linerboards and two types of fiber-efficient linerboards were provided to determine effect of cyclic environments on box compression strength.

Box Specification

Corrugation: C Flute, Single-wall

Basis Weight (linerboard / medium / linerboard) (lb / 1000 ft^2):

- 69-lb standard / 33-lb / 69-lb standard (Box A)
- 58-lb regular fiber-efficient / 33-lb / 58-lb regular fiber-efficient (Box B)
- 90-lb standard / 33-lb / 90-lb standard (Box C)
- 69-lb highly fiber-efficient / 33-lb / 69-lb highly fiber-efficient (Box D)

Box Dimension (LxWxD): 14.00" x 10.00" x 8.08"

Box Style: Regular slotted container (RSC)

2. Two types of combined boards, made from standard linerboards and two types of combined boards made from fiber-efficient linerboards were provided to determine the edge crush value for their material physical property specification.

Board Specification

Corrugation: C Flute, Single-wall

Basis Weight (linerboard / medium / linerboard) (lb / 1000 ft^2):

- 69-lb standard / 33-lb / 69-lb standard
- 58-lb regular fiber-efficient / 33-lb / 58-lb regular fiber-efficient
- 90-lb standard / 33-lb / 90-lb standard
- 69-lb highly fiber-efficient / 33-lb / 69-lb highly fiber-efficient

3. Four types of linerboards and corrugating medium were provided to determine basis weight, thickness and ring crush value for their material physical property specification.

Linerboard Specification

Basis Weight (lb / 1000 ft^2) :

- 69-lb standard linerboard
- 58-lb regular fiber-efficient linerboard
- 90-lb standard linerboard
- 69-lb highly fiber-efficient linerboard

Corrugating Medium Specification

Basis Weight (lb / 1000 ft^2): 33-lb

Heavy weight linerboards were selected for use in this study since fiber-efficient linerboards are usually used to replace heavy weight conventional linerboards. In the study, 69-lb standard / 33-lb / 69-lb standard box (box A) was compared with 58-lb regular fiber-efficient / 33-lb / 58-lb regular fiber-efficient box (box B), and 90-lb standard / 33-lb / 90-lb standard box (box C) with 69-lb highly fiber-efficient / 33-lb / 69-lb highly fiber-efficient box (box D). The two box types in each comparison were claimed by the manufacturer to have similar compression strength under standard condition.

PROCESS TECHNIQUES FOR FIBER-EFFICIENT LINERBOARD

Two types of fiber-efficient linerboards were used to manufacture the boxes in this study. They were regular fiber-efficient linerboard (used in box B) and highly fiber-efficient linerboard (used in Box D). According to the manufacturer, the regular fiber-efficient linerboards used in Box B were different from standard linerboards used in Box A and C in the following ways:

1. Addition of a special species of wood fibers e.g., Southern Pine.

These fibers provide more flexibility and are flatter than regular wood fibers (like Douglas Fir). The flexibility and flatness provides added surface area for fiber-to-fiber bonding. The flexibility of fibers allows the fibers to collapse from tube shape to flat ribbon shape during the drying process and thus increases contact area between fibers (Kline, 1982).

2. The use of more refining.

The refining process is a mechanical process that breaks down the ordered structure of the fiber in order to improve fiber-to-fiber bonding.

3. Application of a fiber orientation technique.

With the fiber orientation technique, fibers are forced to run perpendicular to the paper-making machine direction. This eventually causes more fibers to run vertically up and down the panels of a container which results in better compression strength.

4. The use of more virgin fibers versus recycled fibers.

5. Application of ENP (extended nip press) or high pressure forming technique.

The ENP was used during the papermaking process to press the fibers together under high pressure loads. It creates a denser sheet with more fiber-to-fiber bonding.

The highly fiber-efficient linerboards used in box D were manufactured using the same techniques and processes as used in the regular fiber-efficient linerboards. However, additional refining, beyond what was used for the regular fiber-efficient linerboards was used in manufacturing the highly fiber-efficient linerboards. In addition, a chemical was added to the highly fiber-efficient linerboards to provide extra chemical linkages (covalent bonds). Adding the chemical also imparts wet strength properties to the linerboard.

BOX SET UP

Knocked-down boxes with the manufacturer's joint attached by adhesive (starch adhesive with wet strength resin added) were obtained from a commercial manufacturer of corrugated packaging. The boxes were set up and sealed top and bottom with pressure sensitive tape using 3M adjustable case sealer.

PRE-CONDITIONING

Prior to conditioning all test fiberboard materials and knock-down boxes at TAPPI standard conditions, they were conditioned at a low humidity environment of 70±2F, 35±3% RH for 5 days. After that, they were transferred to condition at TAPPI standard condition of 73 ± 3 F, 50%RH for at least 48 hours before testing.

CYCLIC CONDITIONING

After box set up and pre-conditioning, boxes were transferred to an environmental chamber. Two identical environmental chambers were used. Even though the chambers have temperature (T) and relative humidity (RH) measuring instruments, chamber conditions were manually measured using a psychrometer, model No.566 (Bendix Corporation), which records both RH and T. The measurement was repeated approximately every 12 hours (see Appendix A).

Boxes were rotated through a cyclic condition in 6 days. For each cyclic condition, three different RH and T conditions were combined where each combination was maintained for 2 days (48 hours). Boxes were remained in the same chamber for the entire cyclic condition. Five different cyclic conditions were studied and are as follows:

1) 41 F, 85% RH → 73 F, 50% RH → 41F, 60% RH

2) 99 F, 85% RH → 73 F, 85% RH → 99 F, 85% RH

3) 99 F, 85% RH → 41F, 85% RH → 73 F, 50% RH

4) 99 F, 30% RH → 73 F, 50% RH → 41 F, 85% RH

5) 41 F, 85% RH → 73 F, 50% RH → 99 F, 30% RH

These cyclic conditions were designed to simulate the real-life conditions that boxes are subjected to. Descriptions of the simulation of each RH and T condition (Powers and Witt, 1972) are as follows:

i. 41 F, 85% RH = Refrigeration

ii. 73 F, 50% RH = Controlled room condition (TAPPI standard condition)

iii. 41 F, 60% RH = Nighttime in Spring and Fall in Great Lakes states.

(e.g., Michigan, Illinois and Wisconsin)

iv. 99 F, 85% RH = Daytime in Summer in Central states.

(e.g., Missouri, Kansas and Arkansas)

v. 73 F, 85% RH = Nighttime in Summer in Mid-Atlantic states.

(e.g., Kentucky, Tennessee and Virginia)

v. 99 F, 30% RH = Summer in Southwest states.

(e.g., Arizona, New Mexico and Western Texas)

A total of 24 boxes of each box type were rotated through each cyclic condition in the sequence of T, RH combinations as shown. After being subjected to a cyclic condition, 12 boxes of each box type were tested for compression strength and the moisture content of the box material immediately determined. Another 12 boxes of each box type and condition variable were transferred to re-condition at TAPPI standard condition of 73 F, 50% RH for 2 days and their compression strength and material moisture content determined.

In addition to testing at the five cyclic conditions, all four box types were subjected to two non-cyclic conditions, 73F, 50% RH and 73F, 85% RH, and their compression strength measured. The moisture content of each box material type was also determined following compression testing. To determine the initial box compression strength, boxes were conditioned at 73F, 50%RH. Boxes were conditioned at 73F, 85% RH to determine material moisture gains and effect on box compression strength.

TEST METHODS

Basis Weight and Thickness Measurement

The basis weight and thickness of linerboards and mediums conditioned at TAPPI standard conditions were determined in accordance with ASTM D 646-67-74 and ASTM D 645-67-74, respectively. Ten samples for each board type were used.

Ring Crush Testing

The ring crush values of linerboards and mediums conditioned at TAPPI standard condition were determined in accordance with ASTM D 1165-60-73. Ten samples for each board type were tested.

Edge Crush Testing

The edge crush values of combined boards conditioned at TAPPI standard conditions were determined in accordance with ASTM D 2808-69. Ten samples of each board type were used.

Compression Testing

The compression strength of the boxes were determined in accordance with ASTM D 642-76, using a fixed platen. The fixed platen, as opposed to a floating platen, was used because only the differences in the quality of box materials were examined in this study. If the compression test is performed using the floaten platen, the compression strength value will also reflect the variations of the quality of the box fabrication process. Compression testing was performed using a Lansmont compression tester. The room was conditioned at 73 ± 3 F, $50 \pm 3\%$ RH. During testing, two boxes at a time were transported from the chamber to the compression tester. The distance between the chamber and the compression tester is about 10 meters which takes less than 20 seconds to transport. One box at a time was placed on the lower platen of the tester and the compression test was performed. The upper platen was lowered onto the box until the box collapsed and the maximum load was recorded. The test was usually completed within 1.5 minutes for the lower compression strength boxes and 2.0 minutes for the higher compression strength boxes.

Moisture Content Determination

The moisture content of the box material was determined on each box tested for compression strength. Immediately after compression testing, the top flap of each box was cut into 4" x 4" samples and the moisture content was determined in accordance with ASTM D 644-55.

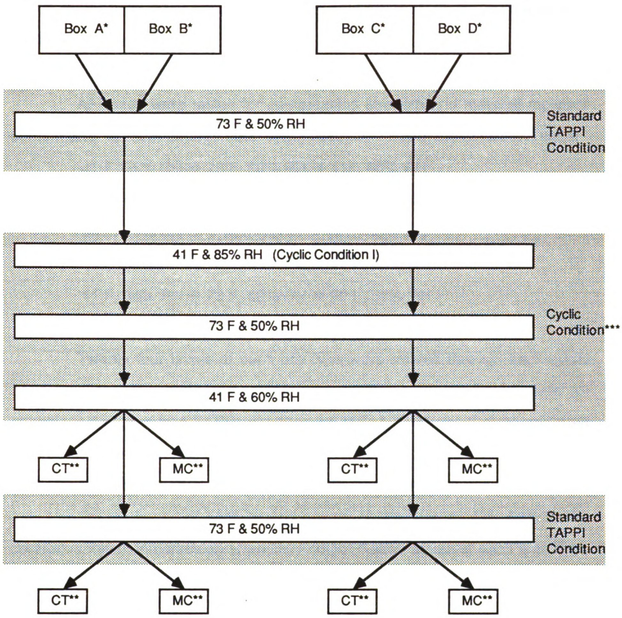
Experimental Design

The testing sequence is shown in Figure 3. A total of 12 boxes of each box type were used for each treatment. Due to the difficulty in maintaining the environmental chamber condition, the experiment was designed in such a way that this variation would be minimized. For each treatment, the 12 boxes were separated into three sets and one set was rotated through each cyclic condition at a time. Thus, four boxes of each box type were rotated through each cyclic condition together and their compression strength and material moisture content determined. The same procedure was repeated three times in order to obtain 12 replicates for each treatment.

Variables Evaluated to Determine Effect on Compression Strength of Box Samples

1. Fiber-efficient linerboards and standard linerboards

The compression strength of boxes made from 58-lb regular fiber-efficient linerboard was compared with the compression strength of boxes made from 69-lb standard linerboard. Another comparison studied was between



CT = Compression Test   MC = Moisture Content Determination

* Eight box samples were used.

** Four box samples were used.

*** i. Cyclic condition I = 41F, 85% RH - 73F, 50% RH - 41F, 60% RH
ii. Cyclic condition II = 99F, 85% RH - 73F, 85% RH - 99F, 85% RH
iii. Cyclic condition III = 99F, 85% RH - 41F, 85% RH - 73F, 50% RH
iv. Cyclic condition IV = 99F, 30% RH - 73F, 50% RH - 41F, 85% RH
v. Cyclic condition V = 41F, 85% RH - 73F, 50% RH - 99F, 30% RH

Note: This procedure was repeated three times in order to obtain 12 replicates for each treatment.

Figure 3 Testing sequence for determining compression strength of boxes and moisture content of box materials.

boxes made from 69-lb highly fiber-efficient linerboard and boxes made from 90-lb standard linerboard.

2. Cyclic conditions

All boxes were tested for compression strength and material moisture content after rotation through each cyclic condition The cyclic conditions were:

- 41 F, 85% RH → 73 F, 50% RH → 41F, 60% RH
- 99 F, 85% RH → 73 F, 85% RH → 99 F, 85% RH
- 99 F, 85% RH → 41F, 85% RH → 73 F, 50% RH
- 99 F, 30% RH → 73 F, 50% RH → 41 F, 85% RH
- 41 F, 85% RH → 73 F, 50% RH → 99 F, 30% RH

3. Re-conditioning

Twenty four boxes of each box type were rotated through each cyclic condition, with 12 being tested immediately. The other 12 boxes were re-conditioned at standard TAPPI condition of 73F, 50%RH for 2 days and their compression strength and material moisture content determined.

4. Standard condition and high humidity condition

Twelve boxes of each box type were conditioned at 73F, 50% RH to determine initial compression strength. Another twelve boxes of each type were conditioned at 73F, 85% RH to determine material moisture gains and effect on box compression strength.

RESULTS AND DISCUSSION

In this study the compression strength of boxes made from fiber-efficient (high-performance) linerboards was examined under cyclic conditions. The compression strength of boxes made from fiber-efficient linerboards was then compared to boxes made from standard linerboards after exposure to the same cyclic conditions. Over 500 corrugated boxes were subjected to five cyclic conditions and their compression strength evaluated. The moisture content of box materials was also determined. After exposure to each cyclic condition, noncompressed boxes were re-conditioned at TAPPI standard conditions (73F, 50% RH) and their compression strength and moisture content determined.

The "basic" physical properties of the box samples, the combined boards and the board components (linerboards and corrugating mediums) used in this study are shown in Table 1.

A 3-factor factorial experiment was conducted to investigate the effect of the experimental variables on box compression strength. Three variables were evaluated in this study. These were:

- Box types (2 types)
  - i. Boxes made from standard linerboards
  - ii. Boxes made from fiber-efficient linerboards
- Cyclic conditions (5 conditions)
  - i. 41 F, 85% RH→73 F, 50% RH→41F, 60% RH

Table 1 Physical properties of the box materials.

	69-lb Standard Linerboard	58-lb Regular Fiber-efficient Linerboard	90-lb Standard Linerboard	69-lb Highly Fiber-efficient Linerboard	33-lb Medium
Basis Weight* ($lb/1000\ ft^2$)	68	59	91	67	33
Thickness* (pt.)	17.9	13.8	22.8	16.6	10.8
Ring Crush* (lb)	96.7	98.6	157.2	137.5	54.2

	Combined Board			
	69-lb Standard Linerboard	58-lb Regular Fiber-efficient Linerboard	90-lb Standard Linerboard	69-lb Highly Fiber-efficient Linerboard
Edge Crush Test** (Weyerhaeuser Method) (lb/in)	42.1	44.3	58.2	54.3

* An average of 10 test samples

** An average of 15 test samples

Note: See Appendix A for standard deviation of the data.

ii. 99 F, 85% RH → 73 F, 85% RH → 99 F, 85% RH

iii. 99 F, 85% RH → 41F, 85% RH → 73 F, 50% RH

iv. 99 F, 30% RH → 73 F, 50% RH → 41 F, 85% RH

v.41 F, 85% RH → 73 F, 50% RH → 99 F, 30% RH

- Re-conditioning

i. After cyclic condition exposure

ii. Re-conditioning

A 3-way analysis of variance (ANOVA) for a completely randomized design was performed (Appendix C). Boxes made from 69-lb standard linerboards were compared with boxes made from 58-lb regular fiber-efficient linerboards. The results of the ANOVA test suggest that there were 2-way interactions between box types and cyclic conditions, and cyclic conditions and re-conditioning. A 2-way interaction means that the two variables act together to affect the compression strength. In addition, there was a 3-way interaction between all three variables. This indicates that the three variables act together to affect the compression strength. The second comparison was between boxes made from 90-lb standard linerboards and boxes made from 69-lb highly fiber-efficient linerboards. The results of the ANOVA test shows that there was a 2-way interaction between cyclic conditions and re-conditioning.

I. BOXES MADE FROM STANDARD LINERBOARDS VS BOXES MADE FROM FIBER-EFFICIENT LINERBOARDS

In this study, examination of the difference in loss of strength due to the cyclic conditions, and comparison of the final compression strength after exposure to the cyclic conditions were conducted to compare the potential stacking performance of two box types under cyclic conditions. Boxes made from 69-lb standard linerboards was compared with boxes made from 58-lb regular fiber-efficient linerboards, and boxes made from 90-lb standard linerboards with boxes made from 69-lb highly fiber-efficient linerboards.

I.I LOSS OF STRENGTH

69-lb Standard Linerboard vs 58-lb Regular Fiber-Efficient Linerboard

The average compression strength of boxes made from 69-lb standard linerboards (box A) and boxes made from 58-lb regular fiber-efficient linerboards (box B), after exposure to TAPPI standard conditions (73F, 50% RH) and five cyclic conditions are summarized in Table 2. Based on an Analysis of Variance (ANOVA) (Ott, 1989), the initial compression strength of boxes held at TAPPI standard conditions was significantly different between the two box types at 99.9% confidence level (Appendix D). Box B was 166$\pm$60 lbs (approximately 13%) higher in compression strength than box A, after conditioning at 73F, 50% RH. The average box compression strength loss due to cyclic conditions was compared using a t-test analysis (Gill, 1978) (Appendix E). The results from the analysis are shown in Table 3. At a confidence level of 99%, significant differences between the two box types were found under cyclic conditions I, II, III and IV. Box B experienced significantly greater loss of strength than box A. For cyclic condition V, the results showed a marginally significant difference in the loss of strength between both box types at a confidence level of 90%. The loss of strength for each box type is shown in Table 3. A graphical presentation of the loss of strength is shown in Figure 4.

The 58-lb regular fiber-efficient linerboard used in box B contains less fibers than the 69-lb standard linerboard used in box A. However, box B has higher compression strength than box A by 166+60 lbs, after conditioning at

Table 2 Compression strength values of boxes made with 69-lb standard linerboard and boxes made with 58-lb regular fiber-efficient linerboard.

Box Type	Storage Condition*	Compression Strength (lbs)**	Std. Deviation
69-lb Standard (Box A)	TAPPI standard	1249	78.8
	Cyclic condition I	1054	71.2
	Cyclic condition II	976	77.7
	Cyclic condition III	1120	44.0
	Cyclic condition IV	738	29.7
	Cyclic condition V	1226	87.9
58-lb Regular Fiber-Efficient (Box B)	TAPPI standard	1415	63.4
	Cyclic condition I	1128	82.2
	Cyclic condition II	978	67.1
	Cyclic condition III	1176	59.6
	Cyclic condition IV	761	58.2
	Cyclic condition V	1336	45.9

* TAPPI standard = at 73F, 50%RH
Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

** An average of 12 test samples.

Table 3 Results from the analysis of difference analyzing loss of strength between boxes made with 69-lb standard linerboard (box A) and boxes made with 58-lb regular fiber-efficient linerboard (box B) for each cyclic condition.

Storage Condition*	t-test value**	Loss of Strength (lbs) 69-lb Standard (Box A)	Loss of Strength (lbs) 58-lb Fiber-efficient (Box B)
Cyclic condition I	3.14	195±64	287±62
Cyclic condition II	5.60	273±66	437±55
Cyclic condition III	3.76	129±54	239±52
Cyclic condition IV	4.88	511±24	654±51
Cyclic condition V	1.91	23±34	73±47

* Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

** Calculated t-value for the difference in strength loss between boxes made with standard linerboard and boxes made with regular fiber efficient linerboard.
Critical t-value = 2.819 at confidence level of 99%
= 1.717 at confidence level of 90%

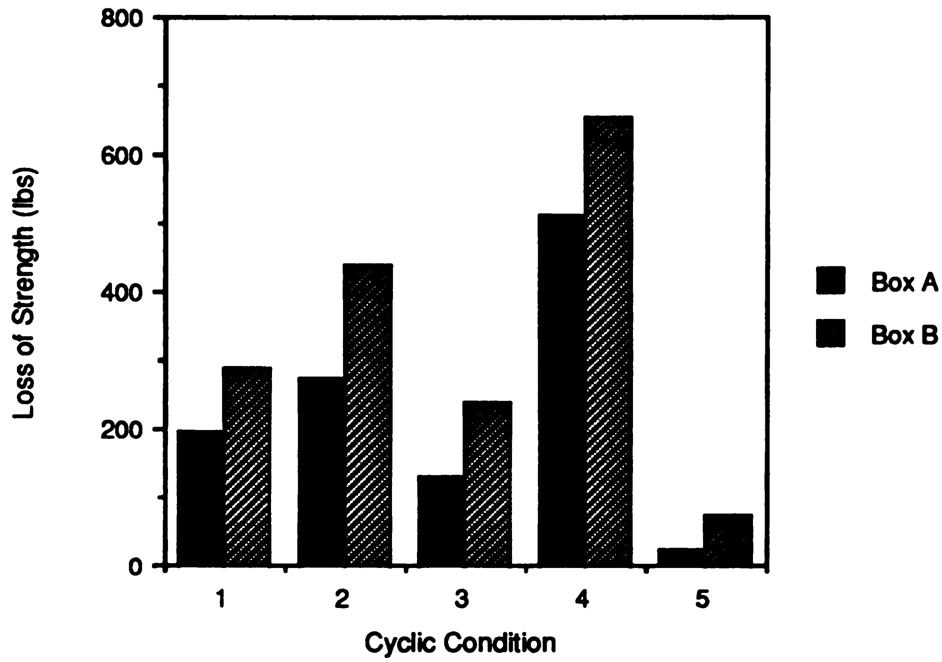


Figure 4 Difference in loss of strength between box A and box B.

73F, 50% RH. This extra strength in the regular fiber-efficient linerboard was obtained by the special techniques used in the papermaking process. The techniques are: (1) the use of more refining than that used for standard linerboard, (2) addition of special species of fibers e.g., Southern Pine fibers, (3) application of a fiber orientation technique, (4) the use of more virgin fibers, and (5) the extended nip press technique.

The refining process is a mechanical process that breaks down the ordered structure of the fiber to expose more hydroxyl groups for fiber-to-fiber bonding (Kline, 1982). The strength of the hydrogen bond that forms between two hydroxyls is fixed and the only way to increase the strength of a sheet of paper is to increase the number of hydrogen bonds between fibers. Therefore, more refining adds strength by increasing the fiber-to-fiber bonding. The Southern Pine fibers added in regular fiber-efficient linerboard provide more flexibility and are flatter than regular fibers (e.g., Douglas Fir) that are used in standard linerboards. The flexibility and flatness provide added surface area for fiber-to-fiber bonding. The flexibility of fibers allows the fibers to collapse from tube shape to flat-ribbon shape during the drying process which results in more contact area between fibers. The extended nip press technique used during papermaking presses the fibers together under a high pressure load. This creates a denser sheet with more fiber-to-fiber bonding. Therefore, the strength in regular fiber-efficient linerboard is increased due to the greater number of hydrogen bonds between fibers.

Hydrogen bonds are a intermolecular force and their strength can be dramatically reduced by the presence of water (Kaufman, 1977). Water tends to disrupt the hydrogen bonds between molecular chains and thus reduces the intermolecular forces. As a result, when the regular fiber-efficient linerboards were exposed to the cyclic conditions with high relative humidity conditions, a significant number of hydrogen bonds were probably lost. This most likely caused the large reduction in compression strength when boxes made from regular fiber-efficient linerboards were subjected to the cyclic conditions.

90-lb Standard Linerboard vs 69-lb Highly Fiber-Efficient Linerboard

The average compression strength of boxes made from 90-lb standard linerboards (box C) and boxes made from 69-lb highly fiber efficient linerboards (box D), after exposure to TAPPI standard conditions and five cyclic conditions are summarized in Table 4. The initial compression strengths of the two box types, after subjection to TAPPI standard conditions, were found to be marginally different by an ANOVA analysis at a confidence level of 93% (Appendix F). Box C was 77$\pm$82 lbs (approximately 5%) higher in compression strength than box D. The average compression strength loss after exposure to cyclic conditions was also compared. The statistical procedure used to determine the difference in strength loss between these two box types was the same as previously described for comparing box A and box B. The analysis is detailed in Appendix G. The results from the analysis (Table 5) indicated that at a confidence level of 90% there were only marginally significant differences in loss of strength between the two box types under cyclic condition I, IV and V and no significant differences under cyclic conditions II and III. A graphical presentation of the difference in strength loss is shown in Figure 5.

Although the 69-lb highly fiber-efficient linerboard used in box D contains less fibers than the 90-lb standard linerboard used in box C, box C had slightly higher compression strength than box D. The highly fiber-efficient linerboard's strength was aided by the same special techniques used in the regular fiber-efficient linerboard (box B). In addition to these techniques, a chemical was added to impart wet strength properties to the linerboard. The

Table 4 Compression strength values for boxes made with 90-lb standard linerboard and boxes made with 69-lb highly fiber efficient linerboard.

Box Type	Storage Condition*	Compression Strength (lbs)**	Std. Deviation
90-lb Standard (Box C)	TAPPI standard	1674	103.6
	Cyclic condition I	1297	99.5
	Cyclic condition II	1166	92.0
	Cyclic condition III	1451	94.5
	Cyclic condition IV	1007	61.1
	Cyclic condition V	1649	91.8
69-lb Highly Fiber-Efficient (Box D)	TAPPI standard	1597	90.1
	Cyclic condition I	1305	102.6
	Cyclic condition II	1143	87.7
	Cyclic condition III	1405	184.4
	Cyclic condition IV	855	62.4
	Cyclic condition V	1571	138.0

* TAPPI standard = at 73F, 50%RH
Cyclic condition I = 41F, 85%RH ➔ 73F, 50%RH ➔ 41F, 60%RH
Cyclic condition II = 99F, 85%RH ➔ 73F, 85%RH ➔ 99F, 85%RH
Cyclic condition III = 99F, 85%RH ➔ 41F,85%RH ➔ 73F, 50%RH
Cyclic condition IV = 99F, 30%RH ➔ 73F, 50%RH ➔ 41F, 85%RH
Cyclic condition V = 41F, 85%RH ➔ 73F,50%RH ➔ 99F, 30%RH

** An average of 12 test samples.

Table 5 Results from the analysis of difference analyzing loss of strength between boxes made with 90-lb standard linerboard (box C) and boxes made with 69-lb highly fiber-efficient linerboard (box D) for each cyclic condition.

Storage Condition*	t-test value**	Loss of Strength (lbs) 90-lb Standard (Box C)	Loss of Strength (lbs) 69-lb Fiber-efficient (Box D)
Cyclic condition I	1.71	377±86	292±82
Cyclic condition II	1.34	508±83	454±139
Cyclic condition III	0.77	259±84	192±123
Cyclic condition IV	1.86	667±72	742±66
Cyclic condition V	1.93	25±83	26±99

* Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

** Calculated t-value for the difference in strength loss between boxes made with standard linerboard and boxes made with regular fiber efficient linerboard.
Critical t-value = 1.717 at confidence level at 90%
= 2.074 at confidence level at 95%

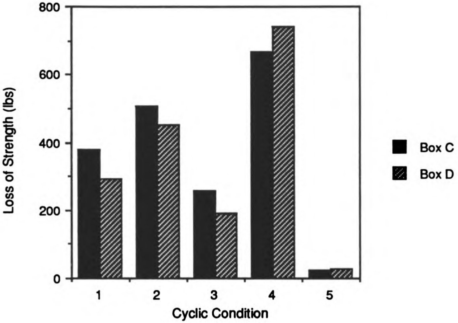


Figure 5 Difference in loss of strength between box C and box D.

chemical also provides extra chemical linkages (covalent bonds) beyond hydrogen bonds. After exposure to the cyclic conditions with high humidity conditions, box C and box D showed only marginally significant difference in loss of strength. This may be because in the highly fiber-efficient linerboard the chemical, acting as a wet strength agent, helped to protect the hydrogen bonds and hold the fibers together when the box was exposed to high humidity. As a result, the box strength was retained. Furthermore, the covalent bonds provided by the chemical are not sensitive to moisture as are the hydrogen bonds. Apparently, the addition of the chemical was an important attribute that enabled the box made from the 69-lb highly fiber-efficient linerboards to retain their compression strength as well as the box made from the 90-lb standard linerboards under the cyclic conditions used in this study.

I.II FINAL COMPRESSION STRENGTH

69-lb Standard Linerboard vs 58-lb Regular Fiber-efficient Linerboard

Final box compression strength after cyclic condition exposure was compared between boxes made from 69-lb standard linerboards (box A) and boxes made from 58-lb regular fiber-efficient linerboards (box B) using a t-test analysis (Appendix H). The results from the analysis are shown in Table 6. At a confidence limit of 95%, a significant difference was found only under cyclic condition I. The final compression strength of box B was 74 ± 65 lbs higher than that of box A. The differences in the final compression strength between the two box types are shown in Table 6. Although box B experienced greater loss of strength than box A under all cyclic conditions, box B's final compression strength was not significantly different from box A's. The final compression strength is an indication of the box stacking ability. The results thus suggest that

Table 6 Results from the analysis of difference in final compression strength between boxes made from 69-lb standard linerboards (box A) and boxes made from 58-lb regular fiber efficient linerboards (box B) for each cyclic condition.

Storage Condition*	t-test value	Difference in Final Compression Strength (lbs)
Cyclic Condition I	2.36	74±65
Cyclic Condition II	0.07	2±61
Cyclic Condition III	1.07	56±109
Cyclic Condition IV	0.49	23±96
Cyclic Condition V	1.75	110±145

* Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

** Calculated t-value for the difference in strength loss between boxes made with standard linerboard and boxes made with regular fiber efficient linerboard.
Critical t-value = 2.074 at confidence level at 95%

the two box types should perform similarly under all cyclic conditions used in this study except cyclic condition I.

90-lb Standard Linerboard vs 69-lb Highly Fiber-efficient Linerboard

The final compression strength of the boxes made from 90-lb standard linerboards (box C) and boxes made from 69-lb highly fiber-efficient linerboards (box D), after subjection to cyclic conditions, were also compared using the t-test analysis (Appendix H). The results from the analysis (Table 7) shows that there was no significant difference under all cyclic conditions except under cyclic condition IV. The final compression strength of box C was 152$\pm$62 lbs higher than that of box D. The differences in the final compression strength for each box type are shown in Table 7. The results indicate that the two box types should perform similarly under all cyclic conditions except under cyclic condition IV.

II. EFFECT OF MOISTURE ABSORPTION

Cellulosic materials respond to shifts in relative humidity differently. They absorb or desorb moisture at different rates (Byrd, 1984). This response can be critical in the performance of a corrugated fiberboard box. Byrd (1984) assumed from his study that increased creep rates (used to predict final box stacking performance) resulted from increased moisture sorption by fiberboards. Therefore, differences in loss of compression strength among the four box types in this study may partially be as a result of the differences in moisture absorption among the box materials.

The moisture content of the different materials used for each box type and held at 73F, 85% RH for 2 days was measured to determine the percent

Table 7 Results from the analysis of difference in final compression strength between boxes made from 90-lb standard linerboards (box C) and boxes made from 69-lb highly fiber efficient linerboards (box D) for each cyclic condition.

Storage Condition*	t-test value	Difference in Final Compression Strength (lbs)
Cyclic Condition I	0.08	8±210
Cyclic Condition II	0.26	23±186
Cyclic Condition III	0.31	46±304
Cyclic Condition IV	2.46	152±62
Cyclic Condition V	0.66	78±243

* Cyclic condition I = 41F, 85%RH ➔ 73F, 50%RH ➔ 41F, 60%RH
Cyclic condition II = 99F, 85%RH ➔ 73F, 85%RH ➔ 99F, 85%RH
Cyclic condition III = 99F, 85%RH ➔ 41F,85%RH ➔ 73F, 50%RH
Cyclic condition IV = 99F, 30%RH ➔ 73F, 50%RH ➔ 41F, 85%RH
Cyclic condition V = 41F, 85%RH ➔ 73F,50%RH ➔ 99F, 30%RH

** Calculated t-value for the difference in strength loss between boxes made with standard linerboard and boxes made with regular fiber efficient linerboard.
Critical t-value = 2.074 at confidence level at 95%

moisture gain. In Table 8, the percent moisture gains of the four materials are shown and a graphical presentation is shown in Figure 6. An ANOVA analysis suggested that the moisture gains by box materials used for the 69-lb standard linerboards (box A) and box materials used for the 58-lb regular fiber efficient linerboards (box B) were significantly different at 99% confidence level (Appendix I). The box B material absorbed more moisture than the box A material. The higher moisture gain in box B was at least in part responsible for its greater compression strength loss when compared with box A.

The difference in moisture gain by the box materials used for the 90-lb standard linerboards (box C) and box materials used for the 69-lb highly fiber-efficient linerboards (box D) was found to be significant at a confidence level of 99% (Appendix J). The box D materials absorbed less moisture than the box C materials. This may be a factor influencing the marginal difference in strength loss between the two box types. The lower moisture gain in box D is probably due to an addition of the wet strength chemical in the 69-lb highly fiber-efficient linerboard. The chemical imparts wet strength properties to linerboard and provides added covalent bonds which are not sensitive to moisture as are the hydrogen bonds. Thus, the addition of the chemical was probably partially responsible for the marginal difference in loss of strength between box C and box D.

III. <u>EFFECT OF CYCLIC CONDITIONS</u>

To determine the significance of the cyclic conditions on the compression strength of each box type, an Improved Bonferroni t-test (Gill, 1990) was used to compare the initial box compression strength after exposure to TAPPI standard conditions with the box compression strength after exposure to the cyclic

Table 8 Percent moisture gain of box materials held at 73F, 85%.

Box Type	%Moisture Content at 73F, 50%RH	at 73F, 85%RH	% Moisture Gain
Box A	7.13	13.01	82.0±3.0
Box B	7.12	13.32	87.0±2.0
Box C	6.90	13.07	89.5±2.5
Box D	7.00	12.84	83.5±2.5

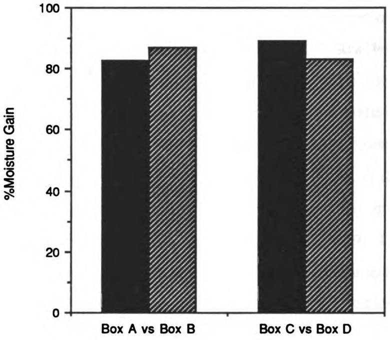


Figure 6 Percent moisture gain for the four different box materials.

conditions for all four box types. A significant difference was found at the 99% confidence level (Appendix K) for all four box types. The cyclic conditions used in this research caused significant reduction in compression strength. The reduction in compression strength due to exposure to the cyclic conditions for each box type is shown in Table 9.

The largest reduction in box compression strength occurs as a result of exposure to cyclic condition IV (99F, 30%RH → 73F, 50%RH → 41F, 85%RH). It is probably the final condition (41F, 85%RH) that most adversely affected box strength. The box materials subjected to cyclic condition IV contained the highest moisture content (Table 10). The presence of moisture in a corrugated fiberboard causes a decrease in fiber-to-fiber bonding. A decrease in fiber-to-fiber bonding generally results in low compression strength and hence negatively affects box stacking performance (Byrd, 1989). Therefore, it is highly probable that the high moisture content of the box materials subjected to cyclic condition IV was at least partially responsible for the reduction in compression strength.

The strength reduction under cyclic condition II (99F,85%RH → 73F,85%RH → 99F, 85%RH) was smaller than that under cyclic condition IV, although the boxes were exposed to high humid environments for the longest period of time. This may have been due to the effect of temperature on the relationship between moisture content of paper and humidity in the atmosphere. If relative humidity is kept constant, an increase in temperature decreases the moisture content of paper (Ott, et al, 1954). In cyclic condition II, the boxes were held at a constant high humidity (85% RH) and the temperature increased to 99F. This resulted in a smaller moisture content. The decreased moisture content caused a smaller reduction in compression strength.

Table 9 Loss of compression strength for each box type after exposure to cyclic conditions.

Storage Condition*	Loss of Compression Strength (lbs)			
	Box A	Box B	Box C	Box D
Cyclic condition I	195±64	287±62	377±86	292±82
Cyclic condition II	273±66	437±55	508±83	454±139
Cyclic condition III	129±54	239±52	259±84	192±123
Cyclic condition IV	511±24	654±51	667±72	742±66
Cyclic condition V	23±34	73±47	25±83	26±99

* Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

<u>Table 10</u> Percent moisture content of box material after exposure to cyclic conditions.

	Cyclic Condition				
	I	II	III	IV	V
Box A	10.7	11.8	8.7	15.5	6.0
Box B	11.3	11.8	8.6	15.3	5.7
Box C	10.8	12.1	8.7	14.6	5.6
Box D	10.5	11.8	8.5	14.7	5.5

The boxes exposed to cyclic condition V (41F, 85%RH → 73F, 50%RH → 99F, 30%RH) experienced the least strength reduction. This is most likely as a consequence of the lower moisture level existing in the box material.

The moisture level in a box material is a very important factor which impacts the box compression strength. The compression strength of a box after exposure to cyclic conditions is substantially affected by the final moisture level in the box material. The reduction in box compression strength and material moisture content after exposure to cyclic conditions for all four box types is shown in Figure 7. A graphical presentation of the relationship between loss of strength and material moisture content is shown in Figure 8. The high correlation coefficient values depict a very strong linear relationship. The figure generally illustrates that the box compression strength decreased as the moisture content increased.

IV. COMPRESSION STRENGTH AFTER RE-CONDITIONING

The average compression strength of all box types, after box re-conditioning (73F, 50% RH) is shown in Table 11. The difference between the compression strength of the boxes after cyclic condition exposure and the compression strength of the boxes after box re-conditioning was found to be statistically significant using an improved Bonferroni t-test at 99% confidence level (Appendix L). The compression strength of the different boxes, after cyclic condition exposure and after re-conditioning is shown in Figure 9. The boxes exposed to cyclic condition I, II, III and IV partially regained their compression strength after re-conditioning at TAPPI standard conditions for 2 days. Since paper is made of cellulose, which is highly hygroscopic, it will absorb and desorb moisture with the environment if the two are not in balance. As water

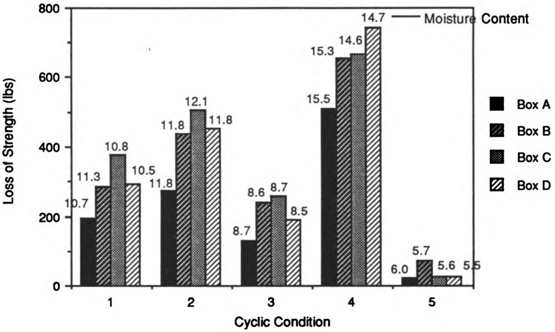
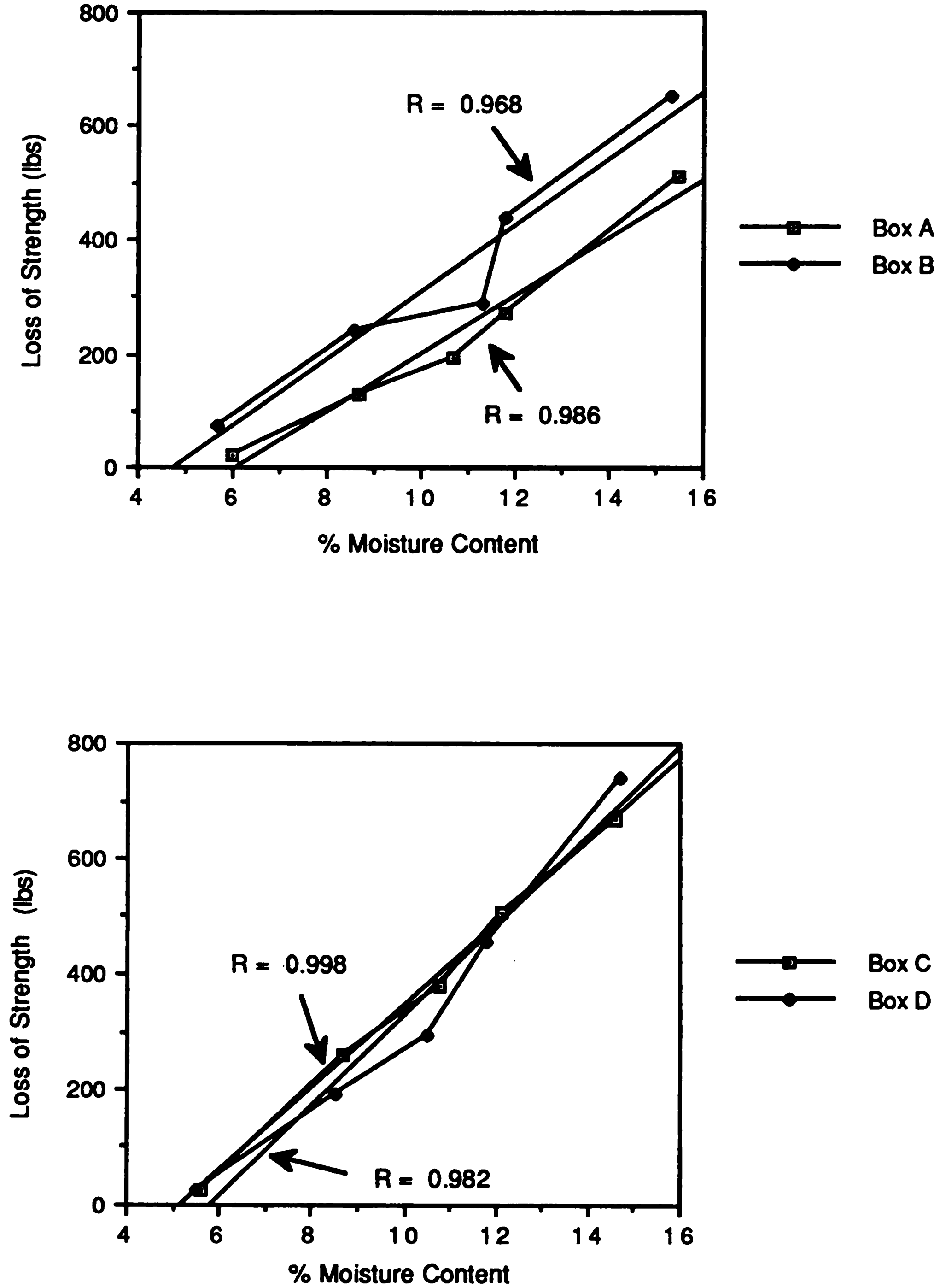


Figure 7 Loss of compression strength and material moisture content after exposure to cyclic condition for all box types



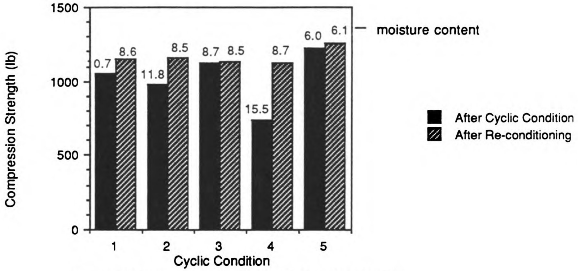
R = Coefficient of Correlation

Figure 8 Relationship between loss of strength and material moisture content.

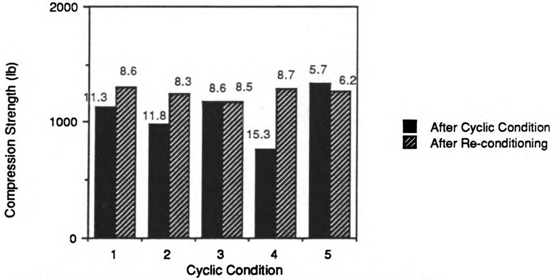
Table 11 Compression strength of all four box types after exposure to TAPPI standard conditions, cyclic conditions and re-conditioning.

Box Type	Storage Condition*	Compression Strength (lbs) Initial	After Cyclic Condition	Re-conditioning
69-lb	73F, 50% RH	1249		
Standard	Cyclic condition I		1054	1154
(Box A)	Cyclic condition II		976	1161
	Cyclic condition III		1120	1129
	Cyclic condition IV		738	1121
	Cyclic condition V		1226	1259
58-lb		1415		
Regular	Cyclic condition I		1128	1300
Fiber	Cyclic condition II		978	1245
Efficient	Cyclic condition III		1176	1173
(Box B)	Cyclic condition IV		761	1296
	Cyclic condition V		1336	1264
90-lb		1674		
Standard	Cyclic condition I		1297	1467
(Box C)	Cyclic condition II		1166	1475
	Cyclic condition III		1451	1482
	Cyclic condition IV		1007	1482
	Cyclic condition V		1649	1598
69-lb		1597		
Highly	Cyclic condition I		1305	1518
Fiber	Cyclic condition II		1143	1508
Efficient	Cyclic condition III		1405	1442
(Box D)	Cyclic condition IV		855	1438
	Cyclic condition V		1571	1561

* Cyclic condition I = 41F, 85%RH → 73F, 50%RH → 41F, 60%RH
Cyclic condition II = 99F, 85%RH → 73F, 85%RH → 99F, 85%RH
Cyclic condition III = 99F, 85%RH → 41F,85%RH → 73F, 50%RH
Cyclic condition IV = 99F, 30%RH → 73F, 50%RH → 41F, 85%RH
Cyclic condition V = 41F, 85%RH → 73F,50%RH → 99F, 30%RH

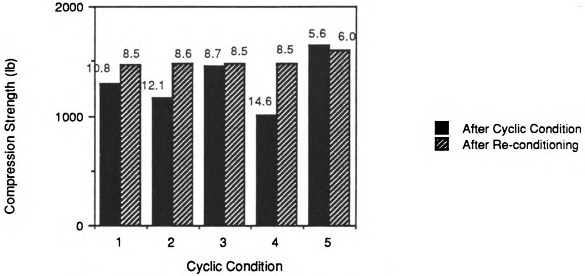


For boxes made with 69-lb standard linerboard (box A).

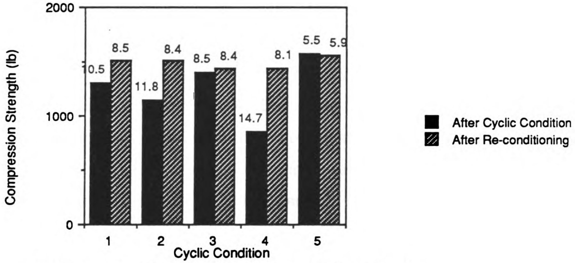


For boxes made with 58-lb regular fiber-efficient linerboard (box B).

Figure 9 Compression strength determined after cyclic condition exposure and after re-conditioning and moisture content of box materials.



For boxes made with 90-lb standard linerboard (box C).



For boxes made with 69-lb highly fiber-efficient linerboard (box D).

Figure 9 (cont'd)

evaporates from the paper, the fibrils (or fiber parts) are drawn together and thus the hydroxyl groups are aligned for bonding (Kline, 1982) (see Figure 10). The box materials exposed to cyclic condition I, II, III and IV contained high moisture levels. They, thus, desorbed water during re-conditioning at TAPPI standard conditions. The moisture content of box materials after cyclic condition exposure and after re-conditioning is shown in Figure 9. As a result, the boxes exposed to cyclic condition I, II, III and IV regained their compression strength due to an increase in hydrogen bonding after re-conditioning at TAPPI standard conditions. All boxes regained part of their compression strength, after re-conditioning for 2 days, probably due to the fact that the box materials had not reached their equilibrium moisture content at the time when the boxes were tested. Table 12 shows moisture content of box materials after initial subjection to TAPPI standard condition and after re-conditioning. The box materials used in this study may need a longer period of time to stabilize their moisture level with the atmosphere.

The boxes exposed to cyclic condition V lost compression strength after re-conditioning (except for box A). Due to the final condition (99F, 30% RH) in cyclic condition V, the moisture content of box materials after subjection to cyclic condition V was very low. The box materials thus absorbed water from the atmosphere when exposed to TAPPI standard conditions. The increase of water in the paper caused a reduction in fiber-to-fiber bonding which results in lower compression strength.

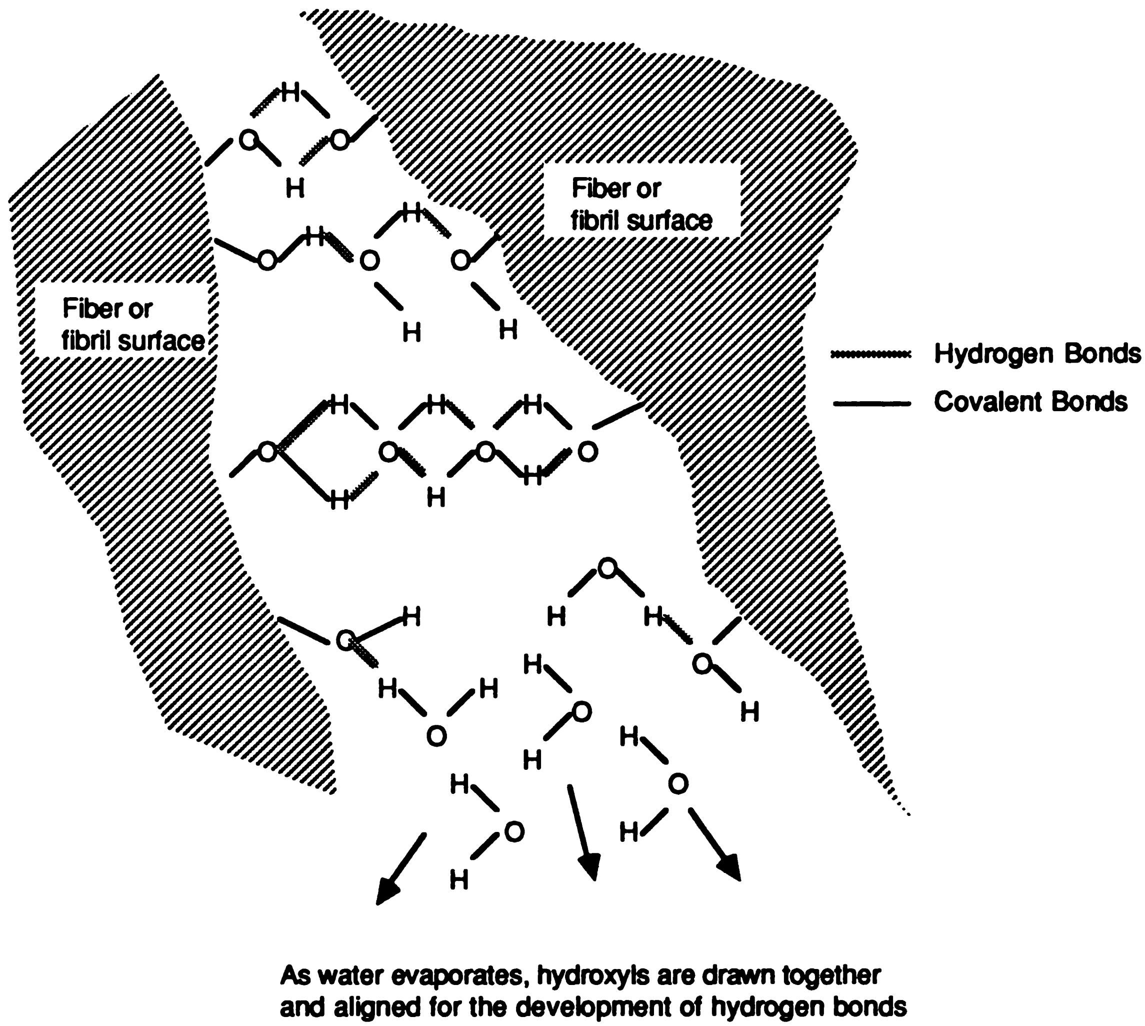


Figure 10 Development of hydrogen bonds from water evaporation.

Table 12 Moisture content of box materials after initial subjection to TAPPI standard condition and after re-conditioning.

Storage Condition*	Moisture Content (%)			
	Box A	Box B	Box C	Box D
TAPPI Standard Condition	7.13	7.12	6.90	7.00
Cyclic Condition I	8.59	8.65	8.47	8.53
Cyclic Condition II	8.53	8.34	8.65	8.36
Cyclic Condition III	8.55	8.58	8.54	8.44
Cyclic Condition IV	8.71	8.75	8.55	8.12
Cyclic Condition V	6.09	6.17	6.00	5.94

* Cyclic condition I = 41F, 85%RH ➔ 73F, 50%RH ➔ 41F, 60%RH
Cyclic condition II = 99F, 85%RH ➔ 73F, 85%RH ➔ 99F, 85%RH
Cyclic condition III = 99F, 85%RH ➔ 41F,85%RH ➔ 73F, 50%RH
Cyclic condition IV = 99F, 30%RH ➔ 73F, 50%RH ➔ 41F, 85%RH
Cyclic condition V = 41F, 85%RH ➔ 73F,50%RH ➔ 99F, 30%RH

SUMMARY AND CONCLUSIONS

The summary of the results from this study are:

1. Boxes made from 58-lb regular fiber-efficient linerboards experienced greater loss of compression strength than boxes made from 69-lb standard linerboards, after exposure to the cyclic conditions used in this study.

2. There were only marginally significant differences in loss of compression strength between boxes made from 69-lb highly fiber-efficient linerboards and boxes made from 90-lb standard linerboards under cyclic condition I (41F, 85% RH ➔ 73F, 50% RH ➔ 41F, 60% RH), IV (99F, 30% RH ➔ 73F, 50% RH ➔ 41F, 85% RH) and V (41F, 85% RH ➔ 73F, 50% RH ➔ 99F, 30% RH) and no significant differences under cyclic condition II (99F, 85% RH ➔ 73F, 85% RH ➔99F, 85% RH) and III (41F, 85% RH ➔ 41F, 85% RH ➔ 73F, 50% RH).

3. There was marginally significant difference in final compression strength between boxes made from 69-lb standard linerboards and boxes made from 58-lb regular fiber-efficient linerboards under cyclic condition I, and no significant difference under cyclic condition II, III, IV and V.

4. The final compression strength of boxes made from 90-lb standard linerboards and boxes made from 69-lb highly fiber-efficient linerboards was not found to be different under all cyclic conditions, except under cyclic condition IV.

5. The differences in moisture absorption among the box materials were found to be at least a partial factor causing the differences in loss of compression strength among the four box types after exposure to the cyclic conditions. Compression strength decreased with an increase in moisture absorption by the box material.

6. All cyclic conditions used in this study caused significant reduction in compression strength for all four box types.

7. The boxes subjected to cyclic condition I, II, III and IV partially regained their compression strength after re-conditioning at TAPPI standard condition (73F, 50% RH) for 2 days, boxes subjected to cyclic condition V lost compression strength after re-conditioning.

The results in this study indicate that although the boxes made from 58-lb regular fiber-efficient linerboards lost more compression strength than the boxes made from 69-lb standard linerboards under cyclic conditions used in this study, they may perform similarly under the cyclic condition II, III, IV and V. No significant differences in final compression strength between the two box types were found. The final compression strength is an indication of the stacking performance of the boxes. The results of the marginal difference in loss of strength and no difference in final compression strength (except cyclic condition IV) suggest that boxes made from 90-lb standard linerboards and boxes made from 69-lb highly fiber-efficient linerboards should perform similarly under cyclic conditions used in this study.

This study demonstrated that even though two types of corrugated fiberboard containers perform similarly in a non-cyclic environment, one may fail before the other in a cyclic environment. One box type may lose its compression strength greater or faster than the other under the cyclic environment. It is thus important to report the stacking performance of the corrugated fiberboard containers under cyclic environments.

APPENDICES

APPENDIX A

Temperature and percent relative humidity in the environmental chambers

Date	Chamber 1 Set Condition	Chamber 1 Cyclic Condition	Chamber 1 Actual Condition	Chamber 2 Set Condition	Chamber 2 Cyclic Condition	Chamber 2 Actual Condition
3-3-90	41F, 85% RH	I	41F, 87% RH			
	"	I	41F, 89% RH			
3-4-90	"	I	42F, 88% RH			
	"	I	41F, 87% RH			
3-5-90	73F, 50% RH	I	72F, 54% RH			
	"	I	73F, 52% RH			
3-6-90	"	I	72F, 53% RH			
	"	I	73F, 51% RH			
3-7-90	41F, 60% RH	I	42F, 65% RH			
	"	I	41F, 62% RH			
3-8-90	"	I	41F, 63% RH			
	"	I	41F, 65% RH			
3-9-90	41F, 85% RH	V	41F, 88% RH			
	"	V	42F, 89% RH			
3-10-90	"	V	41F, 87% RH			
	"	V	41F, 91% RH			
3-11-90	73F, 50% RH	V	73F, 53% RH			
	"	V	72F, 54% RH			
3-12-90	"	V	72F, 54% RH			
	"	V	73F, 52% RH			
3-13-90	99F, 30% RH	V	99F, 34% RH			
	"	V	99F, 32% RH			
3-14-90	"	V	99F, 30% RH	41F, 85% RH	I	42F,85% RH
	"	V	99F, 31% RH	"	I	41F, 87% RH
3-15-90	99F, 30% RH	IV	99F, 31% RH	"	I	41F, 88% RH
	"	IV	99F, 30% RH	"	I	41F, 88% RH
3-16-90	"	IV	99F, 32% RH	73F, 50% RH	I	74F, 54% RH
	"	IV	99F, 31% RH	"	I	73F, 55% RH
3-17-90	73F,50% RH	IV	73F, 53% RH	"	I	73F, 56% RH
	"	IV	73F, 51% RH	"	I	73F, 55% RH
3-18-90	"	IV	72F, 53% RH	41F, 60% RH	I	41F, 64% RH
	"	IV	73F, 50% RH	"	I	42F, 64% RH
3-19-90	41F, 85% RH	IV	41F, 95% RH	"	I	41F, 65% RH
	"	IV	41F, 90% RH	"	I	41F, 65% RH
3-20-90	"	IV	41F, 92% RH	41F, 89% RH	V	41F, 89% RH
	"	IV	42F, 90% RH	"	V	41F, 88% RH
3-21-90	99F, 85% RH	I	99F, 84% RH	"	V	41F, 89% RH
	"	I	98F, 87% RH	"	V	41F, 89% RH
3-22-90	"	I	99F, 87% RH	73F, 50% RH	V	75F, 54% RH
	"	I	99F, 86% RH	"	V	73F, 56% RH
3-23-90	73F, 85% RH	I	73F, 86% RH	"	V	73F, 53% RH
	"	I	73F, 91% RH	"	V	73F, 53% RH
3-24-90	"	I	72F, 89% RH	99F, 30% RH	V	98F, 31% RH
	"	I	73F, 86% RH	"	V	99F, 30% RH
3-25-90	99F, 85% RH	I	99F, 85% RH	"	V	99F, 31% RH
	"	I	99F, 86% RH	"	V	99F, 30% RH
3-26-90	"	I	99F, 87% RH	99F, 85% RH	I	99F, 88% RH
	"	II	98F, 85% RH	"	I	99F, 87% RH
3-27-90	99F, 85% RH	II	99F, 87% RH	"	I	98F, 85% RH
	"	II	99F, 87% RH	"	I	99F, 85% RH

3-28-90	"	II	98F, 86% RH
	"	II	99F, 85% RH
3-29-90	41F, 85% RH	II	41F, 98% RH
	"	II	41F, 95% RH
3-30-90	"	II	42F, 94% RH
	"	II	41F, 95% RH
3-31-90	73F, 50% RH	II	73F, 55% RH
	"	II	74F, 53% RH
4-1-90	"	II	73F, 51% RH
	"	II	73F, 50% RH
4-2-90	99F, 85% RH	I	99F, 86% RH
	"	I	99F, 87% RH
4-3-90	"	I	98F, 85% RH
	"	I	99F, 86% RH
4-4-90	73F, 85% RH	I	75F, 89% RH
	"	I	73F, 89% RH
4-5-90	"	I	73F, 88% RH
	"	I	73F, 89% RH
4-6-90	99F, 85% RH	I	99F, 85% RH
	"	I	99F, 84% RH
4-7-90	"	I	99F, 85% RH
	"	I	99F, 85% RH
4-8-90	99F, 85% RH	II	99F, 85% RH
	"	II	99F, 86% RH
4-10-90	"	II	98F, 86% RH
	"	II	99F, 85% RH
4-11-90	41F, 85% RH	II	41F, 95% RH
	"	II	41F, 92% RH
4-12-90	"	II	42F, 90% RH
	"	II	41F, 93% RH
4-13-90	73F, 50% RH	II	73F, 56% RH
	"	II	74F, 53% RH
4-14-90	"	II	73F, 54% RH
	"	II	73F, 53% RH
4-15-90	99F, 30% RH	IV	99F, 31% RH
	"	IV	99F, 32% RH
4-16-90	"	IV	99F, 31% RH
	"	IV	99F, 34% RH
4-17-90	73F,50% RH	IV	73F, 54% RH
	"	IV	73F, 53% RH
4-18-90	"	IV	72F, 56% RH
	"	IV	73F, 53% RH
4-19-90	41F, 85% RH	IV	41F, 89% RH
	"	IV	41F, 87% RH
4-20-90	"	IV	41F, 90% RH
	"	IV	42F, 92% RH
4-21-90	41F, 85% RH	I	41F, 88% RH
	"	I	41F, 87% RH
4-22-90	"	I	42F, 87% RH
	"	I	41F, 88% RH
4-23-90	73F, 50% RH	I	72F, 56% RH
	"	I	73F, 54% RH
4-24-90	"	I	72F, 54% RH
	"	I	73F, 51% RH
4-25-90	41F, 60% RH	I	41F, 65% RH
	"	I	42F, 66% RH
4-26-90	"	I	41F, 65% RH
	"	I	41F, 64% RH
4-26-90	41F, 85% RH	V	41F, 88% RH
	"	V	42F, 87% RH
4-27-90	"	V	41F, 86% RH
	"	V	42F, 87% RH
4-28-90	73F, 50% RH	V	73F, 55% RH
	"	V	73F, 56% RH
	73F, 85% RH	I	73F, 89% RH
	"	I	73F, 89% RH
	"	I	73F, 91% RH
	"	I	74F, 90% RH
	99F, 85% RH	I	98F, 85% RH
	"	I	99F, 86% RH
	"	I	99F, 88% RH
	"	I	99F, 86% RH
	99F, 85% RH	II	99F, 86% RH
	"	II	99F, 89% RH
	"	II	99F, 87% RH
	"	II	99F, 87% RH
	41F, 85% RH	II	41F, 98% RH
	"	II	41F, 95% RH
	"	II	41F, 94% RH
	"	II	41F, 96% RH
	73F, 50% RH	II	73F, 54% RH
	"	II	73F, 53% RH
	"	II	73F, 51% RH
	"	II	73F, 51% RH

4-29-90	"	V	72F, 54% RH
	"	V	74F, 52% RH
4-30-90	99F, 30% RH	V	99F, 32% RH
	"	V	99F, 32% RH
5-1-90	"	V	98F, 31% RH
	"	V	99F, 31% RH
5-2-90	99F, 30% RH	IV	99F, 32% RH
	"	IV	99F, 33% RH
5-3-90	"	IV	99F, 30% RH
	"	IV	99F, 31% RH
5-4-90	73F,50% RH	IV	73F, 56% RH
	"	IV	73F, 56% RH
5-5-90	"	IV	72F, 52% RH
	"	IV	73F, 53% RH
5-6-90	41F, 85% RH	IV	41F, 92% RH
	"	IV	41F, 90% RH
5-7-90	"	IV	41F, 89% RH
	"	IV	42F, 90% RH
5-8-90	73F, 85% RH	**	73F, 86% RH
	"	"	72F, 87% RH
5-9-90	"	"	73F, 87% RH
	"	"	73F, 86% RH
5-10-90	"	"	74F, 86% RH
	"	"	73F, 86% RH
5-11-90	"	"	73F, 85% RH
	"	"	73F, 87% RH
5-12-90	"	"	73F, 85% RH
	"	"	73F, 85% RH
5-13-90	"	"	73F, 86% RH
	"	"	73F, 87% RH

** Non-cyclic condition at 73F, 85% RH.

APPENDIX B

Results of the physical properties of the box materials.

	69-lb Standard Linerboard	58-lb Regular Fiber-efficient Linerboard	90-lb Standard Linerboard	69-lb Highly Fiber-efficient Linerboard	33-lb Medium
Basis Weight* (lb/1000 ft2)	68	59	91	67	33
Thickness* (pt.)	17.9	13.8	22.8	16.6	10.8
SD =	.18	.20	.50	.15	.26
Ring Crush* (lb)	96.7	98.6	157.2	137.5	54.2
SD =	4.75	4.56	4.32	3.58	2.52

	Combined Board			
	69-lb Standard Linerboard	58-lb Regular Fiber-efficient Linerboard	90-lb Standard Linerboard	69-lb Highly Fiber-efficient Linerboard
Edge Crush Test** (Weyerhaeuser Method) (lb/in)	39.7	44.3	58.9	54.2
SD =	1.9	1.9	3.9	4.7

* An average of 10 test samples

** An average of 15 test samples

APPENDIX C

An analysis of variance for 3-factor factorial experiment.

- For 69-lb standard and 58-lb regular fiber efficient linerboards

Analysis of Variance Table

Source	Degree of Freedom	Sum of Square	Mean Square	F Value	Prob.
Factor A	1	318024.037	310824.037	60.0261	0.0000
Factor B	1	1551880.837	1551880.837	299.6980	0.0000
AB	1	21489.338	21489.338	4.1500	0.0428
Factor C	4	2188003.708	547000.927	105.6364	0.0000
AC	4	43995.192	10998.798	2.1241	0.0788
BC	4	1812765.392	453191.348	87.5200	0.0000
ABC	4	116807.142	29201.785	5.6394	0.0002
Error	220	1139192.750	5178.149		
Total	239	7184958.396			

Factor A = Boxes with 69-lb standard linerboard vs boxes with 58-lb regular fiber-efficient linerboard
Factor B = Compression strength obtained immediately after cyclic conditions vs Compression strength after re-conditioning
Factor C = Cyclic conditions

Critical F-value (1,220) ~ 3.88 at 95% confidence level
Critical F-value (4,220) ~ 2.41 at 95% confidence level

- For 90-lb standard and 69-lb highly fiber efficient linerboards

Analysis of Variance Table

Source	Degree of Freedom	Sum of Square	Mean Square	F Value	Prob.
Factor A	1	66101.204	66101.204	6.5354	0.0112
Factor B	1	2701093.838	2701093.838	267.0558	0.0000
AB	1	38329.537	38329.537	3.7896	0.0528
Factor C	4	4196661.892	1049165.473	103.7305	0.0000
AC	4	126043.442	31510.860	3.1155	0.0161
BC	4	2470086.058	617521.515	61.0540	0.0000
ABC	4	15345.775	3836.444	0.3793	
Error	220	2225155.417	10114.343		
Total	239	11838817.163			

Factor A = Boxes with 90-lb standard linerboard vs boxes with 69-lb highly fiber-efficient linerboard

Factor B = Compression strength obtained immediately after cyclic conditions vs Compression strength after re-conditioning

Factor C = Cyclic conditions

Critical F-value (1,220) ~ 3.88 at 95% confidence level

Critical F-value (4,220) ~ 2.41 at 95% confidence level

APPENDIX D

One way Analysis of Variance for determining difference in initial compression strength between boxes made with 69-lb standard linerboard and boxes made with 58-lb regular fiber efficient linerboard.

Analysis of Variance Table

	Degree of Freedom	Sum of Squares	Mean Square	F-value	Prob.
Between	1	164838.375	164838.375	32.220*	<0.001
Within	22	112552.583	5116.027		
Total	23	277390.958			

Critical F-value = 14.4 at 99.9% confidence level

* Statistically significant

APPENDIX E

A t-test analysis for determining the significance of the difference in strength loss between two box types.

$$t = \frac{\Delta s - \Delta c}{[V(\Delta s - \Delta c)]^{1/2}}$$

$$V(\Delta s - \Delta c) = [V(\Delta s) + V(\Delta c)]$$

$V(\Delta s)$ = (standard error of compression strength at TAPPI condition $)^2$

$V(\Delta c)$ = (standard error of compression strength after cyclic condition $)^2$

Δs = Difference of initial compression strength = $Y_{a1} - Y_{a2}$

Δc = Difference of compression strength after cyclic condition = $Y_{b1} - Y_{b2}$

Y_{a1} = Average compression strength of standard box at TAPPI condition
Y_{a2} = Average compression strength of fiber efficient box at TAPPIcondition
Y_{b1} = Average compression strength of standard box after cyclic condition
Y_{b2} = Average compression strength of fiber efficient box after cyclic condition

<u>Calculation</u>

$$[V(\Delta s - \Delta c)]^{1/2} = [\{(20.65)^2 + (20.77)^2\}]^{1/2}$$

$$= 29.29$$

- Cyclic condition I: $t = 92 / 29.29 = 3.14$
- Cyclic condition II: $t = 164 / 29.29 = 5.60$
- Cyclic condition III: $t = 110 / 29.29 = 3.76$
- Cyclic condition IV: $t = 143 / 29.29 = 4.88$
- Cyclic condition V: $t = 56 / 29.29 = 1.91$

Critical t-value = 2.819 at confidence level of 99%

APPENDIX F

One way Analysis of Variance for determining difference in initial compression strength between boxes made with 90-lb standard linerboard and boxes made with 69-lb highly fiber efficient linerboard.

Analysis of Variance Table

	Degree of Freedom	Sum of Squares	Mean Square	F-value	Prob.
Between	1	3561.042	35651.042	3.786*	0.0646
Within	22	207183.917	9417.451		
Total	23	242834.958			

Critical F-value = 2.95 at 90% confidence level; 4.30 at 95% confidence level

* Statistically significant

APPENDIX G

A t-test analysis for determining the significance of the difference in strength loss between two box types

$$t = \frac{\Delta s - \Delta c}{[\, V(\Delta s - \Delta c)\,]^{1/2}}$$

$$V(\Delta s - \Delta c) = [\, V(\Delta s) + V(\Delta c)\,]$$

$V(\Delta_S)$ = (standard error of compression strength at TAPPI condition $)^2$

$V(\Delta_C)$ = (standard error of compression strength after cyclic condition $)^2$

Δ_S = Difference of initial compression strength = $Y_{a1} - Y_{a2}$

Δ_C = Difference of compression strength after cyclic condition = $Y_{b1} - Y_{b2}$

Y_{a1} = Average compression strength of standard box at TAPPI condition
Y_{a2} = Average compression strength of fiber efficient box at TAPPI condition
Y_{b1} = Average compression strength of standard box after cyclic condition
Y_{b2} = Average compression strength of fiber efficient box after cyclic condition

Calculation

$$[\, V(\Delta s - \Delta c)\,]^{1/2} = [\{ (28.01)^2 + (29.03)^2 \}]$$

$$= 40.34$$

- Cyclic condition I:	t = 69 / 40.34 = 1.71
- Cyclic condition II:	t = 54 / 40.34 = 1.34
- Cyclic condition III:	t = 31 / 40.34 = 0.77
- Cyclic condition IV:	t = 75 / 40.34 = 1.86
- Cyclic condition V:	t = 78 / 40.34 = 1.93

Critical t-value = 1.717 at 90% confidence level; 2.074 at 95% confidence level

APPENDIX H

A t-test analysis for determining the significance of the difference in final compression strength between two box types.

$$t = (U_1 - U_2) \,/\, S_{\bar{y}1 - \bar{y}2}$$

U_1 = Average final compression strength of box A after exposure to cyclic condition

U_2 = Average final compression strength of box B after exposure to cyclic condition

$S_{\bar{y}1 - \bar{y}2}$ = Pooled estimate of variance

<u>Calculation</u>

1. For box A and box B

- Cyclic condition I:	t = (1128 - 1054) / 31.39 = 2.36
- Cyclic condition II	t = (978 - 976) / 29.60 = 0.07
- Cyclic condition III:	t = (1176 - 1120) / 52.38 = 1.069
- Cyclic condition IV:	t = (761 - 738) / 46.20 = 0.49
- Cyclic condition V	t = (1336 - 1226) / 62.92 = 1.75

1. For box C and box D

- Cyclic condition I:	t = (1305 - 1297) / 101.06 = 0.08
- Cyclic condition II	t = (1166 - 1143) / 89.87 = 0.26
- Cyclic condition III:	t = (1451 - 1405) / 146.51 = 0.31
- Cyclic condition IV:	t = (1007 - 855) / 29.77 = 2.46
- Cyclic condition V	t = (1649 - 1571) / 117.20 = 0.66

APPENDIX I

One way Analysis of Variance for determining difference in moisture gains between boxes made with 69-lb standard linerboard and boxes made with 58-lb regular fiber efficient linerboard.

Analysis of Variance Table

	Degree of Freedom	Sum of Squares	Mean Square	F-value	Prob.
Between	1	0.572	0.572	8.086*	0.0094
Within	22	1.555	0.071		
Total	23	2.127			

Critical F-value = 7.95 at 99% confidence level
* Statistically significant

APPENDIX J

One way Analysis of Variance for determining difference in moisture gains between boxes made with 90-lb standard linerboard and boxes made with 69-lb highly fiber efficient linerboard.

Analysis of Variance Table

	Degree of Freedom	Sum of Squares	Mean Square	F-value	Prob.
Between	1	0.313	0.313	8.619*	0.0076
Within	22	0.799	0.036		
Total	23	1.112			

Critical F-value = 7.95 at 99% confidence level
* Statistical significant

APPENDIX K

An Improved Bonferroni t-test for determining the difference between the initial compression strength and compression strength after cyclic conditions.

$$t_B = \{ Y_1 - Y_2 \} / \{ [S^2 / df_1] + [MSE / df_2) \}^{1/2}$$

Y_1 = Average compression strength of boxes held at TAPPI standard condition

Y_2 = Average compression strength of boxes after exposed to cyclic condition

S^2 = Variance of measures in Y_1

MSE = Mean Square Error of measures in Y_2

df1 = degree of freedom for Y1

df_2 = degree of freedom for Y_2

<u>Calculation</u>

- For 69-lb standard and 58-lb regular fiber efficient linerboards

$$t_B = \{ 1332 - 1049 \} / \{ [12060 / 23] + [5178 / 119] \}^{1/2} = 11.87^*$$

- For 90-lb standard and 69-lb highly fiber efficient linerboards

$$t_B = \{ 1636 - 1285 \} / \{ [10558 / 23] + [10114 / 119] \}^{1/2} = 15.05^*$$

Critical t-value = 3.08 at 99% confidence level

APPENDIX L

An Improved Bonferroni t-test for determining the difference between the in compression strength obtained immediately after cyclic conditions and the compression strength after re-conditioning.

$$t_B = \{ Y_1 - Y_2 \} \;/\; \{ [S_1{}^2 / df_1] + [S_2{}^2 / df_2) \}^{1/2}$$

Y_1 = Average compression strength of boxes held at TAPPI standard condition

Y_2 = Average compression strength of boxes after re-conditioned

$S_1{}^2$= Variance of Y_1

$S_2{}^2$ = Variance of Y_2

df_1 = degree of freedom for Y_1

df_2 = degree of freedom for Y_2

<u>Calculation</u>

- For 69-lb standard and 58-lb regular fiber efficient linerboards

$$t_B = \{ 1210 - 1049 \} \;/\; \{ [5178 / 119] + [5178 / 119] \}^{1/2} = 17.3^{*}$$

- For 90-lb standard and 69-lb highly fiber efficient

$$t_B = \{ 1497 - 1285 \} \;/\; \{ [10114 / 119] + [10114/ 119] \}^{1/2} = 16.3^{*}$$

Critical t-value = 3.08 at 99% confidence level

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