EVALUATION OF THE PERFORMANCE OF CORRUGATED SHIPPING CONTAINERS:

VIRGIN VERSUS RECYCLED BOARDS

By

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ABSTRACT

EVALUATION OF THE PERFORMANCE OF CORRUGATED SHIPPING CONTAINERS: VIRGIN VERSUS RECYCLED BOARDS

The compression strength and creep responses of corrugated fibreboard boxes after exposure to high and cyclic relative humidity conditions were studied and compared between boxes made from virgin and recycled liners and mediums which had the same ring crush values. The effect of moisture absorption rate by materials on the creep rate was investigated also.

The results revealed that exposure to the high and cyclic relative humidity conditions used in this study caused significant reduction in compression strength for both box types. The cyclic condition was more detrimental. Recycled boxes experienced greater losses in compression strength than virgin boxes. Significant differences in final compression strength also existed between virgin and recycled boxes for three different humidities. The final compression strength was not only related to moisture content, but also related to the moisture content history of the boxes.

It was found that there were significant differences in creep rate and survival time between virgin and recycled boxes. The cyclic conditions did not cause either a higher creep rate nor an earlier failure for either box type within the testing range.

Dedicated to

This thesis is dedicated to my parents, Yu-hua He and Jun-cheng Zhao for their encouraging letters. Also, to my husband Sammy Cao, for all he has given me.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

APPITA __ Australia Pulp and Paper Industry Technical Association
ASTM ___ American Society for Testing and Materials
BC ______ Back Centre
BC ______ Billerud Cutter
BCT _____ Box Compression Test
BSF _____ Box Strength Factor
CD ______ Cross Machine Direction
CD RCT __ Cross Direction Ring Crush Test
CGC _____ Class Grade Containment
CSRC ____ Compression Strength of Recycled Boxes at Cyclic Humidity (91%-70%-91% RH)
CSREH___ Compression Strength of Recycled Boxes at High Humidity (91% RH)
CSVC ____ Compression Strength of Virgin Boxes at Cyclic Humidity (91%-70%-91% RH)
CSVH____ Compression Strength of Virgin Boxes at High Humidity (91% RH)
CXL _____ Correx Liner Board
DF ______ Double Facer
DOL ____ Duration of Load
ECT _____ Edgewise Compression Test
FBA _____ Fibre Box Association (USA)
FC_______ Front Centre
FEFCO ___ European Federation of Corrugated Board Manufacturers
FPL______ Forest Products Laboratory (USA)
FS _______ Strong Fluting
FU ______ Semichemical medium
H/H______ High Humidity
IPC ______ Institute of Paper Chemistry (USA)
JIS ______ Japanese Industrial Standard
KLB _____ Kraft Liner Board
MD ______ Machine Direction
MEC _____ Equilibrium Moisture Content
MF ______ Melamine Formaldehyde
NF ______ Not Failed

NSSC ____ Neutral Sulfite Semichemical
OCC _____ Old Corrugated Container
PET _____ Polyethylene Terephthalate
PID ______ Proportional Integral Derivative
RB ______ Recycled Boxes
RH ______ Relative Humidity
ROL ____ Rate of Loading
RSC _____ Regular Slotted Container
SCT _____ Short Column Test
SF _____ Single Facer
S/H ______ Standard Humidity
TAPPI ___ Technical Association of the Pulp and Paper Industry
UBC _____ Used Beverage Can
VB ______ Virgin Boxes

1.0 INTRODUCTION

The need to conserve our world timber supply and reduce the problem of solid waste disposal has led to a great interest in expanding the uses for recycled fibres. Economic feasibility is promoting the growth of recycled fibre usage to produce high tonnage products such as corrugated fibreboard containers. Improvement in collection and pulping systems have contributed to a renewed interest in this readily available resource. According to statistical data, nearly 2.8 million tonnes of paper products are consumed annually in Australia. Of this, about 900,000 tons of paper of all types are recycled, which is equivalent to just under a third of all paper used (Industry Commission, 1991).

Despite logical approaches, there is technical concern that containers made from recycled waste paper do not perform as well as virgin boxes in certain applications during storage and transportation as they lack adequate strength. There is concern about long term stacking life of recycled boxes when exposed to high and cyclic RH (Relative Humidity) environments. Products that are shipped regionally, nationally, or internationally may be sent from areas of low humidity conditions to high humidity environments and vice versa. These environmental changes affect the products as well as their packages.

A "cyclic environment" is one where the conditions of temperature and relative humidity fluctuate through several levels. A cyclic environment is used to simulate real-life situations in testing the performance of corrugated fibreboard boxes, because most warehouses are often unable to control the effect of rapidly changing weather conditions, even with climate control systems (Byrd and Koning, 1978).

A cyclic environment has been shown to have an adverse effect on paper's performance and cyclic changes in relative humidity result in a more rapid increase of creep rate than a constant relative humidity condition (Byrd, 1972). Thus loaded boxes exposed to cyclic relative humidity conditions are more likely to have a shorter stacking life than similarly loaded boxes subjected to constant relative humidity environments. A corrugated fibreboard box that performs acceptably in a constant relative humidity condition may not be acceptable in a cyclic environment. For these reasons, it is necessary to evaluate the performance of recycled corrugated fibreboard boxes to assure their proper application and use.

To date, some work has been done based on the recyclability of recycled boxes (Fahey and Bormett, 1982), and the repeated recycling (Koning and Godshall, 1975). These previous works were limited to short-term tests such as box compression tests and drop tests, and did not include the effect of cyclic relative humidity (RH) on box performance, which represents a real-life situation during storage. Some other studies have also been conducted to examine the performance of various kinds of fibreboards under cyclic conditions. Byrd and Koning (1978) studied edgewise compression creep of corrugated fibreboard in a cyclic RH environment of 35%-90%. Considine et al. (1989) investigated the creep behavior of paper board in a cyclic RH environment of 50%-90%. However, their evaluations were limited to the properties of board only. Those properties are different from the properties of corrugated fibreboard boxes made from these materials.

This study has investigated the performance of corrugated fibreboard boxes made from virgin and recycled materials which have the same ring crush value through several different humidity levels. In this study, creep and compression tests were performed to compare the virgin containers with those made from recycled boards.

The aims of this study were:

- to determine the effect of recycled fibre under constant and cyclic RH on the compression strength of corrugated fibreboard boxes.

- to examine creep responses (strain, duration of load, and creep rate) of virgin and recycled corrugated fibreboard boxes under both constant and cyclic RH environments.

- to determine whether the compressive creep rate could be a predictor of duration of load in the high and cyclic relative humidity environments.

This study is intended to contribute to a better understanding of the performance of recycled containers. The results may be used to provide packaged products with better protection during distribution.

2.0 BACKGROUND

2.1 Classification of fibreboard

The grade of paperboard is usually measured on the basis weight, in grams per square meter (often units of measurement are pounds per 1000 ft^2 of sheet, as used in the USA). Together with the caliper, basis weight defines the paperboard.

Classification systems for boards used in corrugated fibreboard boxes have traditionally used the burst strength and the grammage (or basis weight). With the growing importance of box compression, the ECT (Edge Compression Test) was finally recognized as an alternative performance test, based on carrier rules from early 1991 in the USA. The ECT test has been adopted in both FEFCO (European Federation of Corrugated Board Manufacturers) and the USA Carrier Rule Classification Systems.

In Australia, AMCOR Fibre Packaging has developed the CGC (Class-Grade-Containment) rating system which rates boards in terms of both stacking and containment performance.

2.2 Corrugated fibreboard

Corrugated fibreboard consists of two structural components: the corrugated medium and the linerboard. The corrugated medium is the fluted or corrugated center of the board, and the linerboard is the flat material attached to the media, on both sides, or on one side only, as in single faced corrugated fibreboard. Variations in flute height and number of flutes per unit of length define the flute type (A, B, C, E). In addition to single wall, double and triple wall are also in current use.

<u>Corrugated medium:</u>

Virgin corrugated medium is normally manufactured from semichemical processed hardwood. "Hardwood pulp is used rather than softwoods because they cost less and contribute to the strength needed in corrugated medium" (Kline, 1982). For example, hardwood fibres give a higher ring crush value, therefore better ECT strength. In the chemical pulp, the wood is usually treated with chemicals such as alkali or acid to remove the lignin and carbohydrates which hold the cellulose fibres together. In the semichemical process, the pulp is not washed thoroughly as in the chemical pulp process. By not washing or using a strong cook the lignin and other hemicelluloses are left with the fibres. These chemicals help to bond the web of paper and to form the rigid fluted shape needed (Kline 1982). The short hardwood fibres are less flexible than long ones from softwoods and, thus, provide stiffness to the corrugated medium. Corrugated medium is also made from corrugated box plant waste and from old corrugated boxes collected in supermarkets and shopping centers. This is known as recycled medium. Fillers and sizing agents are not needed for the medium, unless wet strength agents are used to provide water resistance.

Linerboard:

Most of the linerboards used for corrugated fibreboard are unbleached Kraft. The Kraft pulping process is basically an alkaline cook. The predominant raw materials used to manufacture linerboard are softwood fibres, though the liner board may contain up to 20% hardwood or secondary fibres (Kline, 1982). Softwood fibres are required to provide the necessary tear and tensile strength to the liner board. Chemical additives may be used to provide water resistance or to increase wet strength of the board. The most common moisture resistant materials used are starch and natural or synthetic resinous material mixed with aluminum sulfate. The aluminum sulfate reacts with the resinous material to form a hydrophobic web interspaced between and attached to the cellulose fibres, whence some resistance to water penetration and wet strength retention is provided to the paperboard (Peleg, 1985).

3.0 LITERATURE REVIEW

Corrugated fibreboard boxes represent the largest segment of the packaging industry in tonnage of materials used (FBA, 1989). The major functions of corrugated fibreboard boxes may be summarized as follows:

- **Protection:** A shipping container must be able to carry a product safely from the producer to the ultimate consumer.

- **Storage:** A fibreboard box is a convenient repository and offers a safe method of storing contents until they are sold.

- **Identification and Advertising:** A shipping container, when printed, serves to identify the contents. It can also provide an advertising billboard for the consumer's product while it is in transit, in storage or on display.

- **Cost:** Corrugated packaging can provide a means of reducing the customer's handling, storing and transportation costs.

(Maltenfort, 1988)

3.1 Recycled fibres in corrugated fibreboard containers

Economic focus within the paper industry is changing. Customer requirements, driven by responses to municipal solid waste management pressures, have led to a significant increase in the recovery and utilization of waste paper. In the United States, the recovery rates for OCC (Old Corrugated Container) have been 51.6% in 1988, and will be approaching 66% by 1995 (Franklin, 1990).

OCC has been an important source of fibre for recycled combination paperboard mills for many years. More recently, OCC has been introduced as a supplement to virgin pulp in liner board and corrugated medium mills. Panther-Cruppe, in Germany, uses 70% recycled material in its manufacturing plants for corrugated board. The remainder consists of kraftliner fibres and this percentage is the minimum necessary to maintain the quality of the board (Verpack-Rundsch, 1990).

In Australia, nearly 2.8 million tons of paper products are consumed annually. Of this, about 900,000 tons of paper of all types are recycled, equivalent to just under a third of all paper used. The level of recovery rate for packaging/industry papers then is at about 51%. The vast majority is used to produce packaging papers which are mostly reprocessed into new packaging products. As a matter of comparison, the recovery rate for aluminum beverage cans is higher than papers (62%), and reflects the ease and cost effectiveness of the operation in which uncontaminated metal can be remelted for further use. In glass manufacture, costs rise more than proportionately where recycled glass (cullet) exceeds about 50%. The recovery rates for Australian most important materials are given in Figure 1.

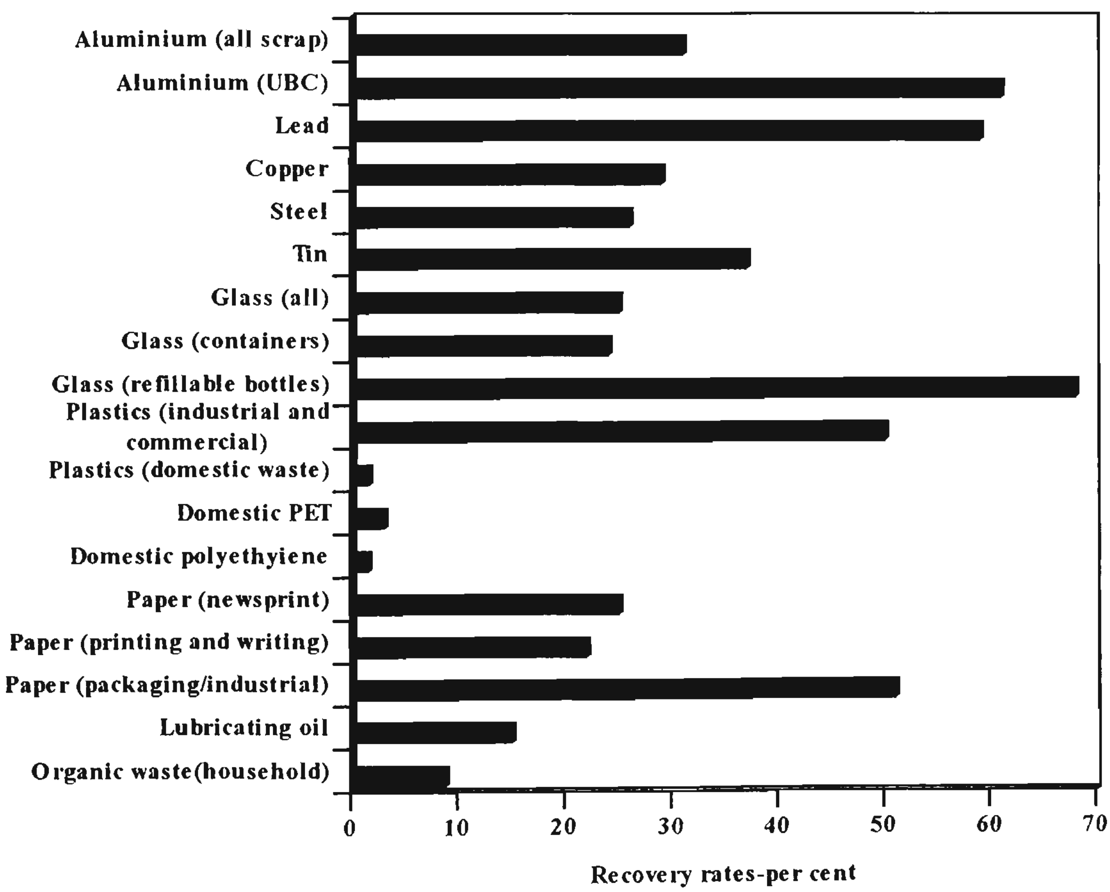


Figure 1. Extent of recycling in Australia (Industry Commission, 1991)

For many years, Australian paper manufacturers have been using substantial quantities of wastepaper. Recycled paper is a good substitute for virgin fibres up to certain proportions. However, packaging papers and boards which contain high proportions of waste have not been labeled "recycled." They have been produced to conform with performance specification.

According to recent figures (Industry Commission, 1991), paper recycling can be cost effective, and can help the environment. It is widely believed that paper recycling will save trees, reduce waste disposal, reduce pollution, save energy and reduce greenhouse gases. With the increased usage of recycled fibres in corrugated boxes, it has become necessary to study the performance of paper, paperboard, and boxes which contain recycled fibres.

Koning and Godshall (1975) studied the properties of liner board, medium, and the combined board made from 100% repeatedly recycled fibre (three cycles) under constant RH and temperature. They studied burst strength, edgewise compressive strength, flexural stiffness, flat crush and scoring of fibreboard. Recycled boxes were tested for compression and impact resistance. They stated that "the greatest loss in strength properties occurs with the first recycle; part of this loss in strength may be attributed to the presence of neutral sulfate semichemical (NSSC) fibres in the liner board and partly to recycling." A further result of this study was that recycling causes a decline of up to 25% in top to bottom compressive strength of container after one cycle.

Fahey and Bormett (1982) investigated the furnish combinations to understand how they affect the recyclability of corrugated fibreboard. They pointed out that "box compressive strength and other properties of combined board, linerboard and corrugating medium were all lower when virgin pulps were replaced with 100% recycled postconsumer corrugated containers." Postconsumer corrugated container is defined as corrugated material discarded by establishments such as stores or by individual residences. Incorporating recycled clean corrugated fibreboard results in losses of properties such as flat crush test, burst strength and compressive strength. These losses generally increase as the percentage of recycled fibre increases. The reductions were attributed to both the drying of the components and the ratio of Kraft pulp to NSSC pulp in the components. Drying on the paper machine is believed to cause irreversible humification of the fibre surface reducing bond sites available when reslushed compared to never dried pulp. Degradation and fibre length shortening also occurs. These effects appear to have a greater effect on changes in combined board and container performance than changes in pulp composition.

Increased Kraft pulp yield to about 55% in the linerboard had no noticeable effect on linerboard or box properties when tested at constant temperature and humidity conditions. Fahey and Bormett also stated that "these tests were made under constant temperature and humidity conditions. Differences in some properties, such as compressive creep, may be expected to be greater if stressed under cyclic humidity conditions".

3.2 Compression strength

The performance requirements of a corrugated shipping container range from the need for advertising appeal to mechanical strength to protect the product. Of the many criteria for boxes, compression strength is generally considered to be the most prominent indicator of final box performance.

The reasons are: (1) compression strength is directly related to warehouse stacking performance, and (2) the laboratory test of box compression strength is readily performed and is useful in the plant for evaluation of the overall quality of the fibreboard materials and the efficiency of the conversion processes (McKee et al., 1961). This study described the top-to-bottom compression behavior of conventional corrugated boxes 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 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 at 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. One of the ways which has been widely used is the compression testing of the empty box.

McKee et al. (1963) devised an equation which is known as the McKee's formula and is used to predict top-to-bottom compression strength of corrugated fibreboard boxes. The expression is as follows:

$$P=5.78P_m(HZ)^{1/2} \tag{1}$$

Where, P = maximal top-to-bottom compressive force, N

P_m = edgewise compressive strength of board, N/m

H = board caliper, m

Z = container perimeter, m

McKee et al. (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.

From McKee's formula we can also see that there is a need for evaluation of the edgewise compression resistance of paperboard. Intuitively, such a test should be well correlated with the test for compression strength of corrugated shipping containers (the CD test for top-to-bottom and MD test for end-to-end compression). The test traditionally used for linking the edgewise compressive strength of the fabricated corrugated paperboard to its paper components is the ring crush test. The ring crush test for paper is standardized by several organizations such as the American Society for Testing and Materials, ASTM D 1164--60, or TAPPI (Technical Association of the Pulp and Paper Industry), Method T818 om-87.

The edgewise compressive strength of the fabricated corrugated board may be predicted by the formula (Peleg, 1985) below:

$$P_m=1.25[\Sigma RC_f \times t_f + \Sigma RC_l] \tag{2}$$

Where, RC_f = ring crush value of flute, N

RC_l = ring crush value of liner, N

t_f = appropriate take-up factor of the flute

The take-up factors t_f, i.e. the ratios of the length of unfluted to fluted corrugating medium, are 1.54, 1.33, 1.45 for A, B, and C flutes, respectively.

The constant factor 1.25 in Eq. (2) was suggested by Wolf (1974). He found that the edgewise compressive strength of the fabricated corrugated board (by TAPPI standard) was on the average 25% higher than that predicted by the combined sum of the ring crush strength of the liners and fluting mediums. This difference is predictable, since the edgewise compressive strength of the fabricated board incorporates the supportive structure of the gluing lines.

According to McKee et al. (1961), in the central region of each panel, the board carries less load than the board near the edges, nevertheless, 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 analyses 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, components of 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, i.e., 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 highest box compression strength.

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

3.3 Test methods related to compression strength

Individual components, combined board and box criteria can be used to predict, before the box is manufactured, how much compression strength it will have (Maltenfort, 1988). The need for such procedures has increased due to increased use of corrugated boxes. There is a number of methods which are 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 can not 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 APPITA 800s-87, 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 10 ± 3 mm/min until the box collapses.

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 the final box performance. Moreover, it is the most important input into McKee's formula, 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 the test procedure one finds that, 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 perpendicularly 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 currently used (Stott, 1988). These methods include the TAPPI method (T811om-88 & T822 om-89), ASTM standard (ASTM 2808-69, reapproved 1990) the FEFCO test method no. 8, Australia Standard (As 1301.444s-88), the JIS (Japanese Industrial Standard) method (JIS 0402), the FPL (Forest Products Laboratory) proposal, the IPC (Institute of Paper Chemistry-USA) proposal and the Weyerhaeuser method. There is no agreed standard testing method for worldwide classification of corrugated fibreboard packaging. The test methods vary according to sample preparation techniques, test conditions and acknowledged failure modes. Samples may be of varying size due to flute structure, varying geometry such as necked down with triangular cuts, necked down with circular cuts, rectangular, rectangular with flaps, and rectangular with some type of fixation. Some testing methods emphasize the importance of a specific failure, for example, that the rupture occurs in the center of the sample. In addition, there are arguments for and against the method used for cutting samples (saw or billerud), and for coating, waxed edge or no coating.

The different testing methods do not produce directly comparable results. According to D'Auria and Marchese (1986) the test results fell into two groups. TAPPI and the proposed FPL and IPC methods gave similar and relatively high results, while FEFCO, JIS, and Weyerhaeuser results were similar to each other at a lower level. The FEFCO method using the Billerud Cutter is referred to as FEFCO BC. In comparing the TAPPI and FEFCO BC methods, Stott (1988) concluded that FEFCO BC methods provided results that were an average 12% lower than those produced by the TAPPI method. Stott (1988) also purported 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. 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 results correlate strongly with results of other test methods that use more elaborate and expensive techniques.

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 directions 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 in RSC may 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.

The two most commonly used methods to measure flexural stiffness are the four-point beam test and the three-point beam test. The number in each case refers to the number of points of contact between the test rig and the test piece.

The loading arrangement used in the three point method introduces shear strains in the medium, the effect being most pronounced for short spans and becoming less noticeable at long spans. The four point method uses a loading arrangement designed to eliminate shear forces throughout the board area under test.

In the four-point test (TAPPI T820 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:

$$\mathrm{D} = \frac{1}{16}\frac{PL^3a}{YwL} \tag{3}$$

Where, D = flexural stiffness, Nm

P = sum of the two weights, N

Y = sum of the deflection of the two weights, m

L = distance between the bottom support anvils, m

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

w = width of the specimen, m

3.4 Effect of atmosphere on strength properties of corrugated boxes

Because the board is hygroscopic, the strength properties of corrugated board products are dependent on the ambient temperature and relative humidity. More precisely, it is the actual moisture content in the corrugated material, regardless of how it has been obtained, which affects the strength (Markstrom, 1988). It is therefore important that laboratory testing takes place in the same test atmosphere if the tests are to be reproducible and comparable between different laboratories. It is also important that the conditioning to 23°C and 50% RH always takes place by starting from about 30% RH, the so called pre-conditioning, in order to attain a reproducible equilibrium moisture content. This is because of the moisture hysteresis effect on the fibre material. Differences of more than 1.5 percentage units can be obtained because of the moisture hysteresis effect (Markstrom, 1988). Internationally, it has been decided that the correct equilibrium moisture content is that which is obtained on absorption (Markstrom, 1988). For accurate conditioning a pre-conditioning in a very dry atmosphere is therefore necessary. Figure 2 shows the moisture content of liner and fluting as a function of the relative humidity and the hysteresis phenomenon of paper. Figure 3 presents the changes in compression strength of board components at different moisture contents.

The moisture content of paper has an important effect on its properties (Kline, 1982). Normally, paper contains about 5% moisture when it is dry. Since paper is made of cellulose, which is highly sensitive to moisture, 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 (1960) 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 can be 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 chemicals 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 fibres 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 fibres 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 fibres of the fibreboard. 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 fibres and cause reduction of box compressive strength.

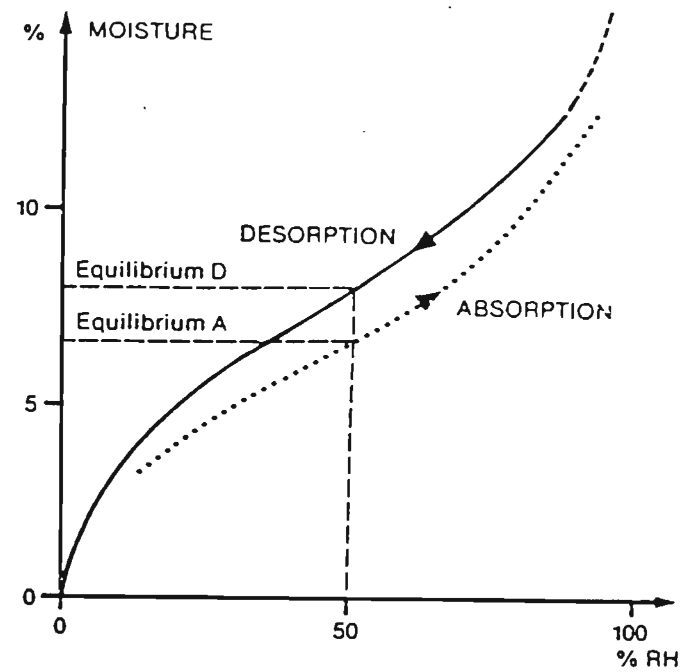


Figure 2. The moisture content of liner and fluting as a function of the relative humidity (Markstrom, 1988)

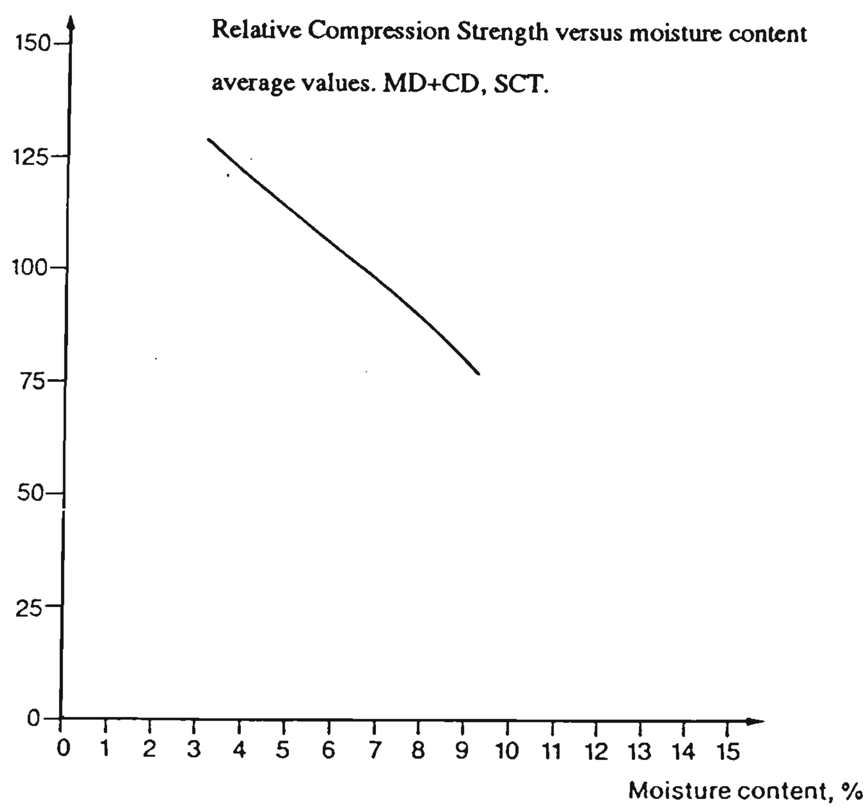


Figure 3. The compression strength of liner and fluting as a function of the moisture content, % (the compression strength at 50% RH has been set to 100 for all grades) (Markstrom, 1988)

Kellicutt (1960) 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. As a rule of thumb it can be said that the strength decreases by 8% if the moisture content increases by 1% unit. The rule of thumb is however valid only within approximately 4% of the equilibrium moisture content at 23°C, 50% RH (Markstrom 1988). A relationship between compressive strength and moisture content was developed by Kellicutt (1951) as follows:

$$Y = b(10)^{3.01X} \tag{4}$$

Where, Y = compressive strength of box, N

b = compressive strength at zero percent moisture content, N

x = moisture content

Kellicutt (1951) found that boxes made from different materials reacted in essentially the same way for specific increase 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:

$$P = P_1 \frac{(10)^{3.01X_1}}{(10)^{3.01X_2}} \tag{5}$$

Where, P = compressive strength to be determined, N

P_1 = known compressive strength, N

x_1 = moisture content for box with P_1 compressive strength,

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

Other strength properties which are strongly affected by the moisture content are the tensile stiffness and the bending stiffness of corrugated board. The effect of relative humidity 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 changes the paper equilibrium moisture content

(EMC), and (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 terms 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 absorption or desorption isotherm, (2) It would eliminate the difficulty in maintaining fixed temperature and RH conditions, and (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 that study, boxes were held at -17.8 °C and -31.7°C, and their compression strength was compared with those 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 fibres 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. Freeze-thaw cycling did not have substantial effect on compression strength of frozen boxes.

3.5 Creep

The process by which a static or "dead" load gradually deforms and eventually collapses a box is known as creep (Maltenfort, 1988).

During the creep process, due to the viscoelastic behavior of paper, the response of the box to a stress or strain is time dependent, i.e., the longer the time, the lower the load sustained.

Creep of regular slotted containers when top loaded by a dead weight for prolonged periods was investigated by Kellicutt and Landt (1951), Moody and Skidmore (1966) and by Koning and Stern (1977).

The total time, from load application to failure, at a given relative humidity environment, depends strongly on the dead weight applied. Kellicutt and Landt (1951) indicated that when the dead loads represented a fairly large percentage of compression test values, slight changes in the amount of dead load applied to a box changed the duration considerably. They also found that "loads that approached the static compression strength of the box caused failure usually within minutes. Dead loads which were about 60 percent of static compressive strength extended the duration to about a month. For dead loads that are less that 75 percent of the machine test load, each decrease of about 8 percentage points in the ratio of the dead load to the static compressive strength results in extending the time of failure by crushing about eight times."

The Figure 4 presents the percentage of ultimate compression load applied in terms of dead weight as a fraction of total yield force in a quasi static compression test. The portion of the curve marked A B corresponds to dead weights near compressive yield force. It is seen that a container may carry 80 percent of yield force for 2.5 hr, 72 percent for a day, 63 percent for 10 days and only 55 percent for long term storage , say 3 months.

Figure 5 shows typical creep behavior of regular slotted containers as reported by Moody and Skidmore (1966).

Three distinctive creep regions were identified as follows:

(1) Primary creep region, characterized by rapid container deflection immediately following application of load. It has nothing to do with load duration, only represents the general elasticity of materials.

(2) Secondary creep, beginning after the creep rate turns into a nearly constant rate or linear deflection rate region.

(3) Tertiary creep region, where the creep rate increases rapidly and failure follows shortly thereafter.

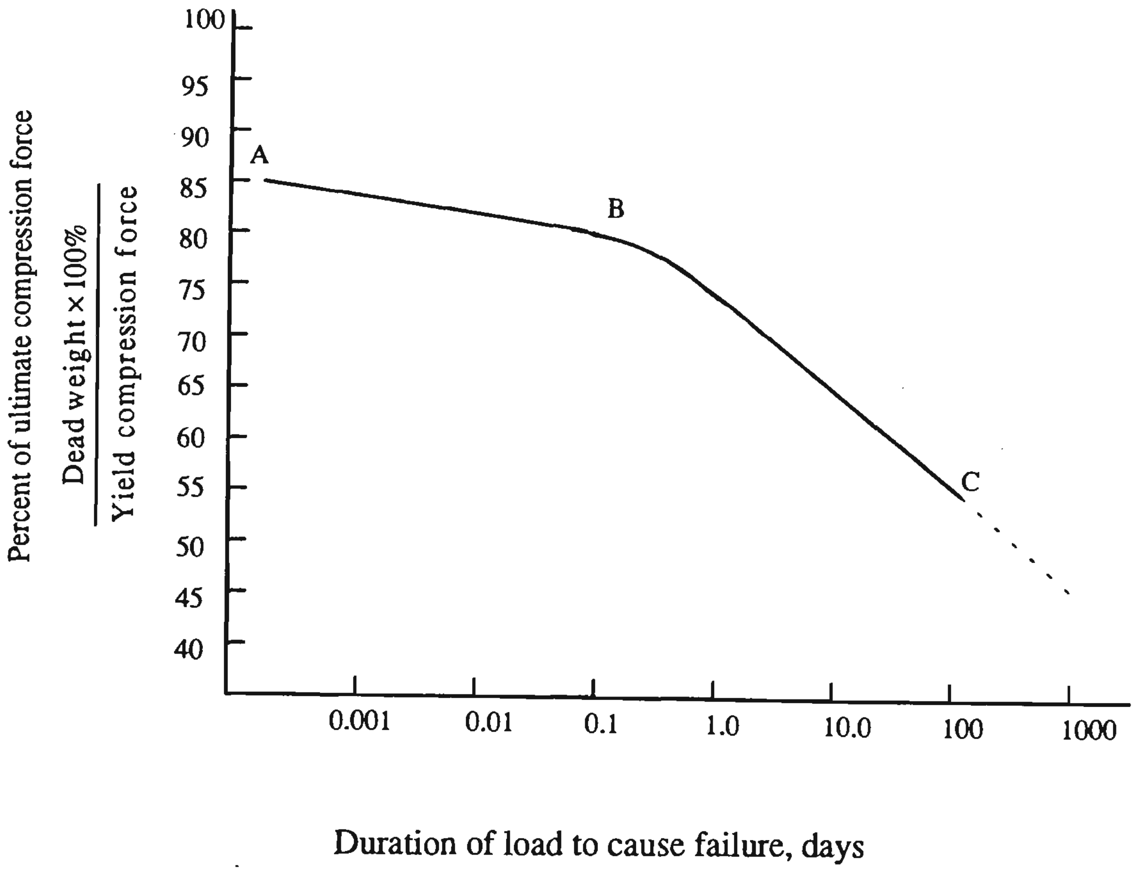


Figure 4. Duration of load tests of corrugated fibreboard containers in different atmospheres with various dead loads (Kellicutt and Landt, 1951)

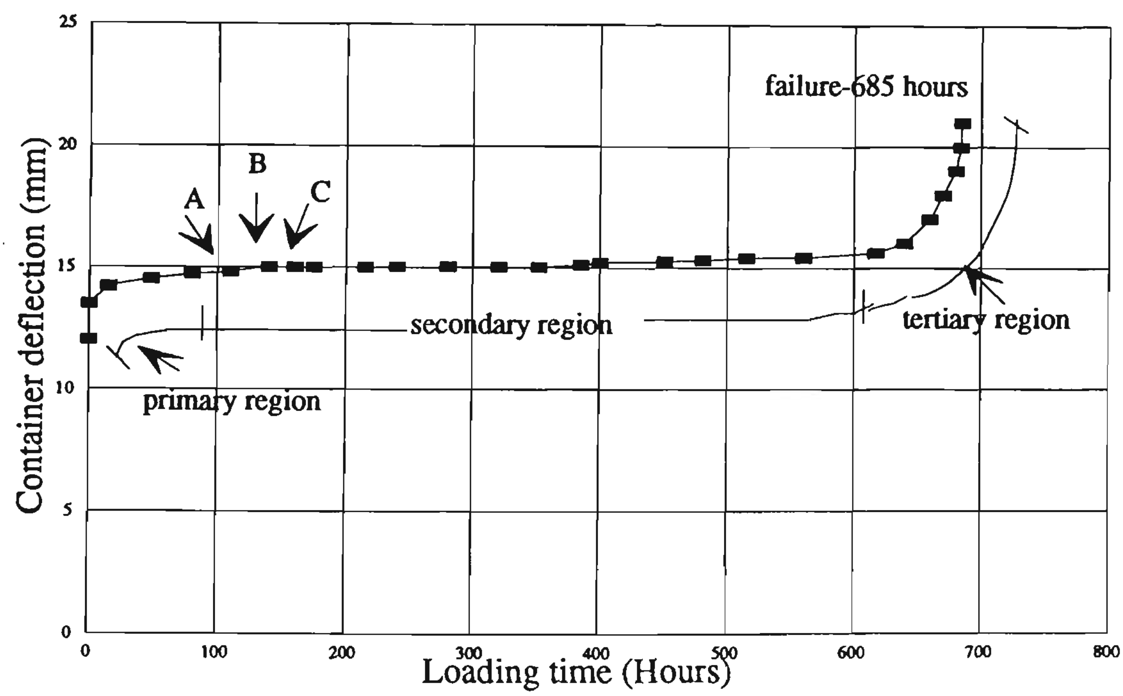


Figure 5. Typical creep properties of regular slotted containers (Moody and Skidmore, 1966)

Koning and Stern (1977) established an empirical relationship linking the duration to failure τ of dead loaded RSC containers in terms of creep rate C_r in the secondary creep region.

$$\tau = 4998 / C_r^{1.038} \tag{6}$$

Where, τ = duration of the load, hours

C_r = secondary creep rate, mm/mm/hr$\times 10^6$

This equation expresses the essentially power form of the secondary creep region as shown in Figure 6 (Figure 6 is in a log-log scale). It suggests it is possible to estimate long term stacking performance of corrugated fibreboard containers using only relative short term dead load tests (few hours).

Stott (1959) studied creep behavior of corrugated boxes extensively. He investigated the relationship between load levels and survival time at four moisture content levels, 5.5%, 10.0%, 13.5%, and 19.5% and showed that when moisture content increased, the load levels versus survival time decreased significantly. He also concluded that moisture has a greater effect on stacking strength (dead loading) than on compression strength (dynamic loading), the stacking strength at 10% moisture being approximately twice that at 17.5%.

During the study of long term stacking, almost all of the researchers pointed out the great deviations of data recorded. Moody and Skidmore (1966) and Koning and Stern (1977) stated that the great variations reported by all authors are partly the result of variations in the compression resistance of the boxes. Thielert (1984) investigated the relationship of load-stacking life of two different types of normal, commercially available corrugated board boxes under 90%, 80%, and 60% of the maximum compression strength at 20°C, 65% RH and found that the distribution of stacking life was not gaussian. However, the probability distribution of lifetimes was approximated by a logarithmic normal distribution.

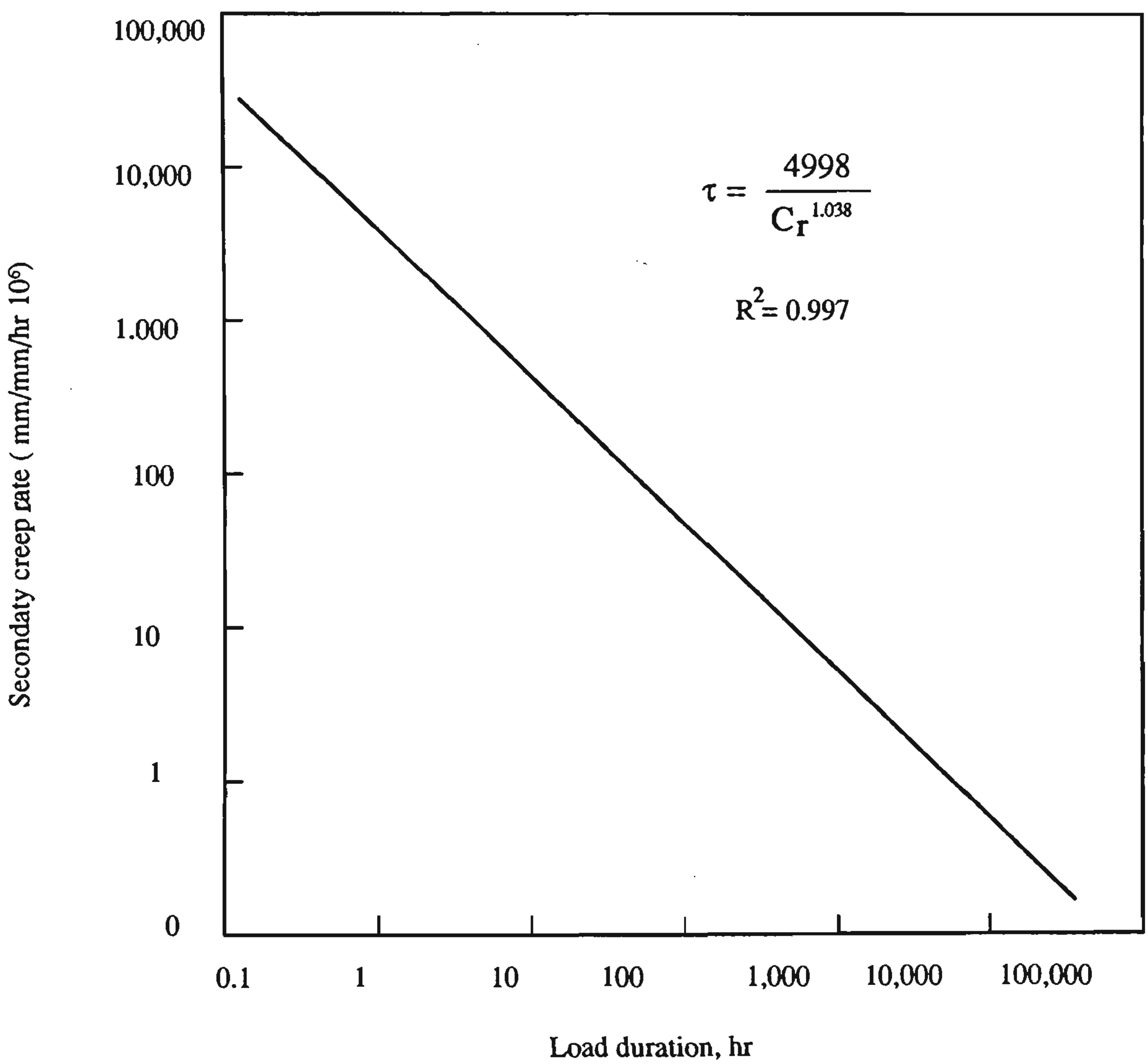


Figure 6. Secondary creep rate versus load duration (Koning and Stern, 1977)

3.6 Caulfield's Theory

Due to the viscoelastic behavior of paper, the mechanical properties are time dependent. One of the notable Characteristics of this material is that when it is loaded to a constant stress level considerably below its normal breaking stress, it will nevertheless break if that stress is maintained over a long enough time. This phenomenon has been called the duration-of-load (DOL) phenomenon. A second phenomenon is called the rate of load (ROL). In this phenomenon, the measured strength of the material increases as the rate at which the material is stressed increases.

Using the theory of absolute rates of chemical processes, Caulfield (1985) demonstrated that there is a linear relationship between the failure load and the logarithm of rate of loading (ROL) in a ramp test (Eq. 7). Furthermore, he showed that a similar relationship applied for a constant load and logarithm of duration of load (DOL) or time to failure (the slopes are the same but negative) (Eq. 8), and most importantly, he provided the mathematical formalism connecting DOL and ROL behavior (Eq. 9). Using this connection, he stated, one can predict how long a material will support a constant deadload stress (DOL) from measurements of strength as a function of rate of stressing in a linear-ramp loading experiment (ROL).

Caulfield's theory is based on chemical kinetics combined with transfer of work and energy. The kinetics approach makes the assumption that rupture is determined completely by the magnitude and nature of the deformation preceding rupture and that the elucidation of the role of creep in the processes leading to failure is the essential problem.

The guiding principle behind the chemical kinetics approach to an understanding of rupture is the idea that straining process itself is, or contains within it, a process of failure that becomes unstable at a time (pre)determined by the straining process, thus ending in rupture.

When this theory is used in predicting DOL behavior, Caulfield effectively assumes that the creep-rupture hypothesis holds true. That is, there is an upper limit that the localized strain deformation can reach, above which the material can no longer support the stress and the material fails.

According to Caulfield, after a series of calculation and ROL experiments, i.e., a series of tests with different load rates, one should be able to write an expression indicated by Eq.7:

$$f = c+k \ln(v) \tag{7}$$

Where, f = failure load, N

c = constant, N

k = slope of the straight line in a Lin-log diagram, N

v = load rate, N/s

For a DOL or constant load experiment, Caulfield showed that the relation between the constant load, "L", and the time to failure "t_f", was given by

$$L = C - k \ln (t_f) \tag{8}$$

Where, L = constant load, N

t_f = time to failure, s

C = constant, N

Obviously, the magnitude of the slope is the same but opposite in sign to that of the ROL behavior. The relationship that ties these two expressions together was shown by Caulfield to be :

$$C-c = k \ln (k) \tag{9}$$

Using Eq (8) and Eq.(9), "t_f" under constant dead load "L", can be predicted by:

$$t_f = \exp ((C-L)/k) = \exp ((c+k \ln(k)-L)/k) \tag{10}$$

Caulfield selected Douglas-fir as an example and proved his theory was valid for wood in bending.

3.7 The effect of cyclic condition on paper properties

Stacking life of corrugated containers is reduced by exposure to high relative humidity. A previous study (Byrd and Koning, 1978) indicated that exposure of compression-loaded corrugated fibreboard to cyclic RH changes is even more detrimental than exposure to a constant high RH. Because most warehouses do not have controlled RH environments, cyclic RH is representative of real-life situation in which corrugated fibreboard containers are used. In the study of the compressive creep response of paper in cyclic relative humidity environment, Byrd (1972) investigated creep behavior of paper in a changing relative humidity environment. The short column corrugated fibreboard specimens were subjected to edgewise compressive loads during exposure to both cyclic (90%-35%-90%) and constant (90%) RH environments. The short RH cycle was 140 min. 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 same study showed that 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 conditions. This behavior is called mechanosorptive effect, because it can't be explained by the superposition of mechanical load response and sorption response.

Byrd and Koning (1978) studied the edgewise compression creep of corrugated fibreboard made from various materials, in cyclic (90%-35%-90%) RH and constant (90%) RH environments. The cycles used were 3 hr vs. 24 hr. The materials of virgin, recycled, high-yield and roughwood southern pine (American) pulp were selected for their study. In comparing the relationship of creep rates of various materials in both constant and cyclic RH environments, the constant 90% RH creep rates did not vary substantially for any of the corrugated fibreboard specimens. Conversely, in cyclic RH conditions, significant differences in creep rates between these specimens were found.

Byrd (1984) stated that since different cellulose 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.

Results showed that liner board made from high-yield pulp sorbed moisture much faster than virgin liner board did. Sorption rates and lignin contents were found to be related (as the lignin content in pulp is increased, the sorption rate rises). The recycled liner board was an exception to this phenomenon. Increasing recycled content reduced the rate of moisture sorption due to the irreversible humification effects which occurred in the paper drying (refer to P7).

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.

3.8 Distribution Environment

Variations in humidity and temperature can and do occur during transportation, in warehouses, and even in retail stores. It happens not only during a year or month, but also during a period of a day. Diurnal cycle is the meteorology term which indicates the variations of temperature and humidity during an average day (a period of 24 hours).

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. As examples, Figure 7 and Figure 8 show wide fluctuations of outdoor relative humidity (RH) for Darwin, North Territory between 1979-1988, at a month interval of a year and 3 hours interval each day respectively (measured by the National Climate Center Australia Bureau of Meteorology). Figure 9 shows the humidity changes of a warehouse at Amcor, based on 24 hours cycle. The difference between the highest and lowest humidity is about 65% RH.

In addition to the daily variation of humidity and temperature, corrugated containers also experience the variation of humidity and temperature caused by different regions and storage conditions. In many cases, shipping containers are moved from low to high humidity environments and vice versa.

For example, if corrugated shipping containers are sent from Melbourne to Singapore in February, the humidity change is expected to be from 50%-75% RH to 95% RH.

Figure 10 is an example of boxes failed. Those shipping containers were shipped from New Zealand to Melbourne. The boxes were taken from a cold storage room where the humidity was 90% RH and placed in an aircraft where the humidity was much lower than 90% RH. Obviously these boxes experienced a lot of humidity changes, and also, some failure.

As a result of the weather fluctuations, and the lack of elaborate moisture control systems in many manufacturing plants, the variations in transportation and storage conditions, most corrugated containers experience moisture sorption and desorption during their service lives. Therefore, cyclic condition is a condition which better represents the real life.

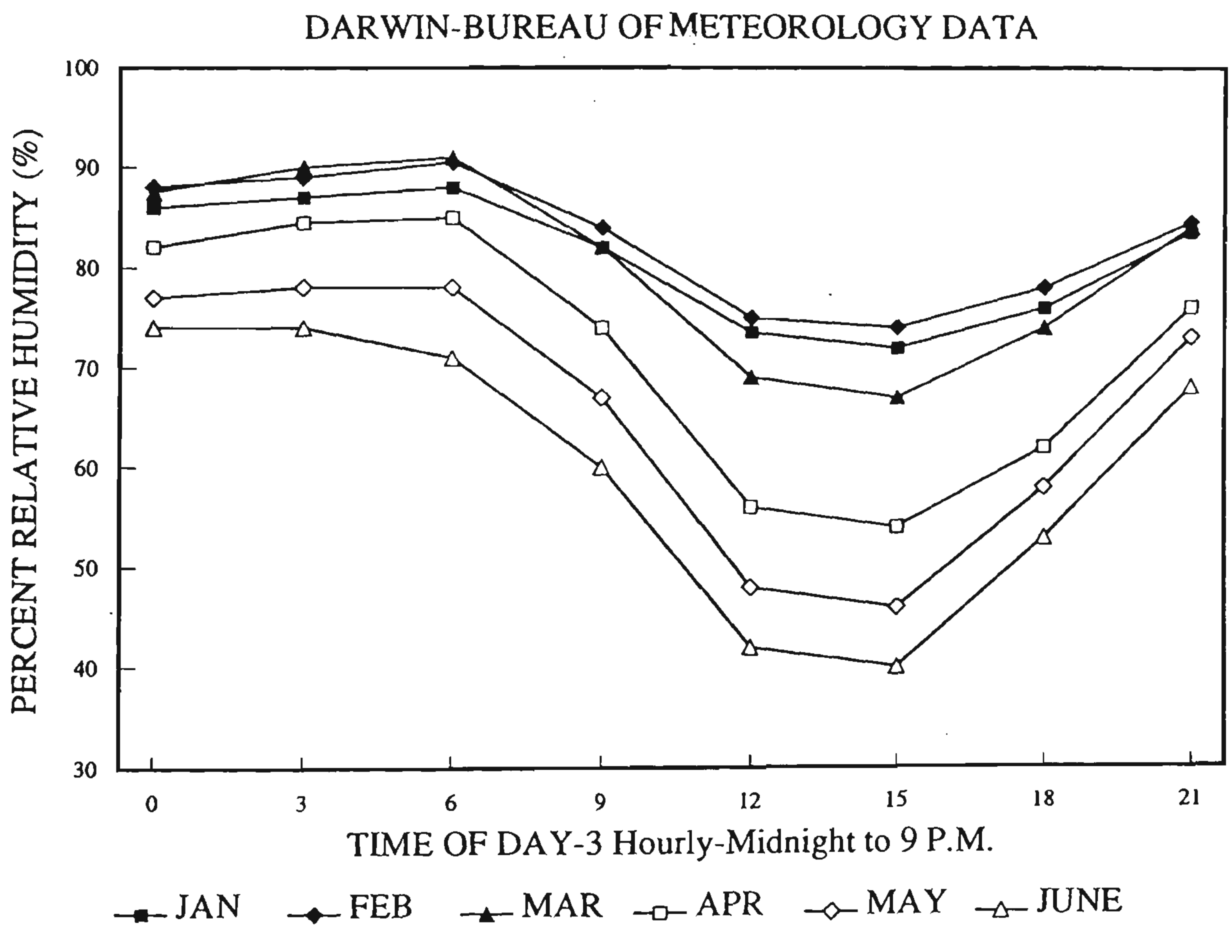


Figure 7. Outdoor relative humidity for Darwin (3 hours interval each day) (National Climate Center Australia Bureau of Meteorology, 1991)

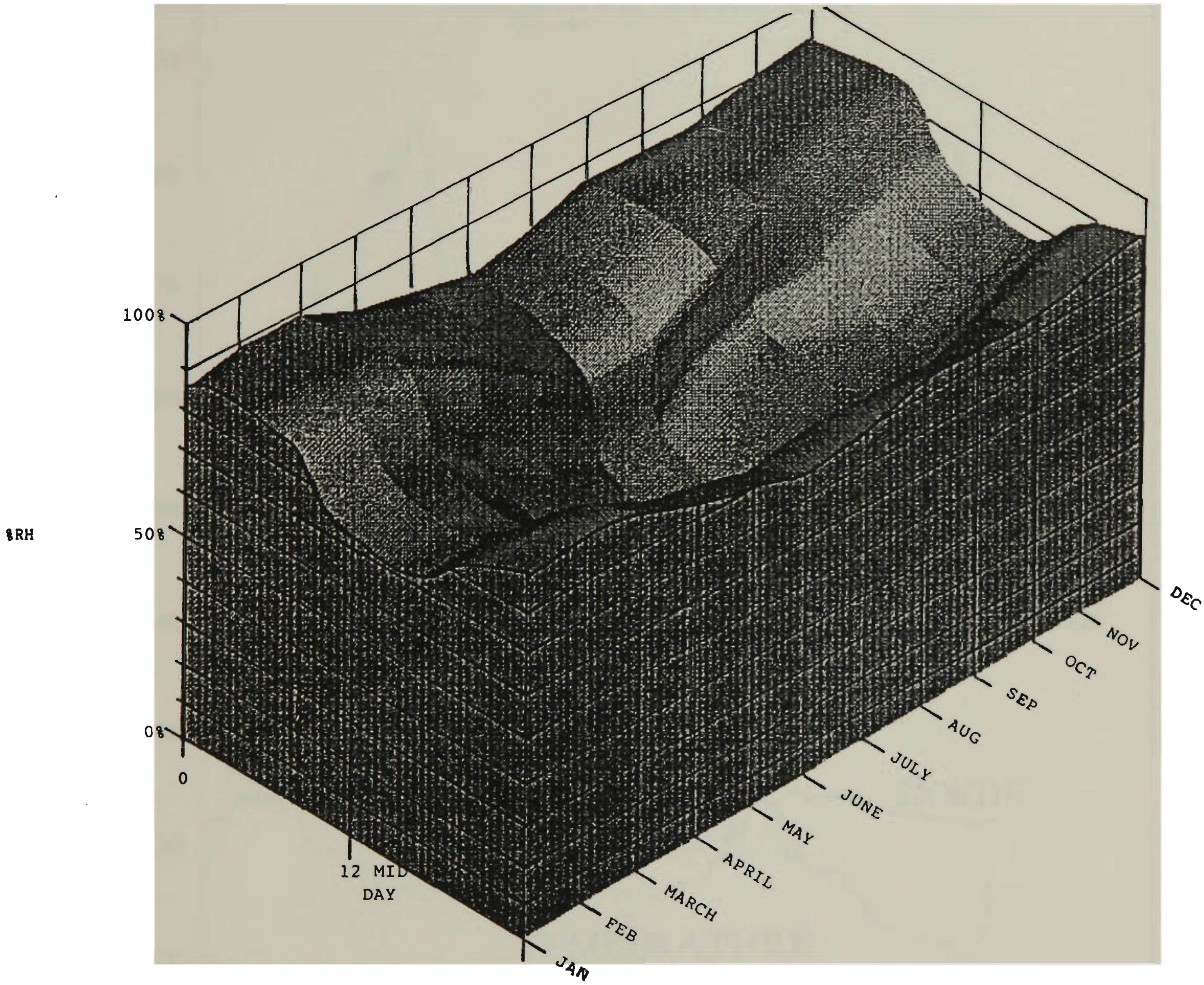


Figure 8. Outdoor relative humidity for Darwin (a month interval of a year)
(National Climate Center Australia Bureau of Meteorology, 1991)

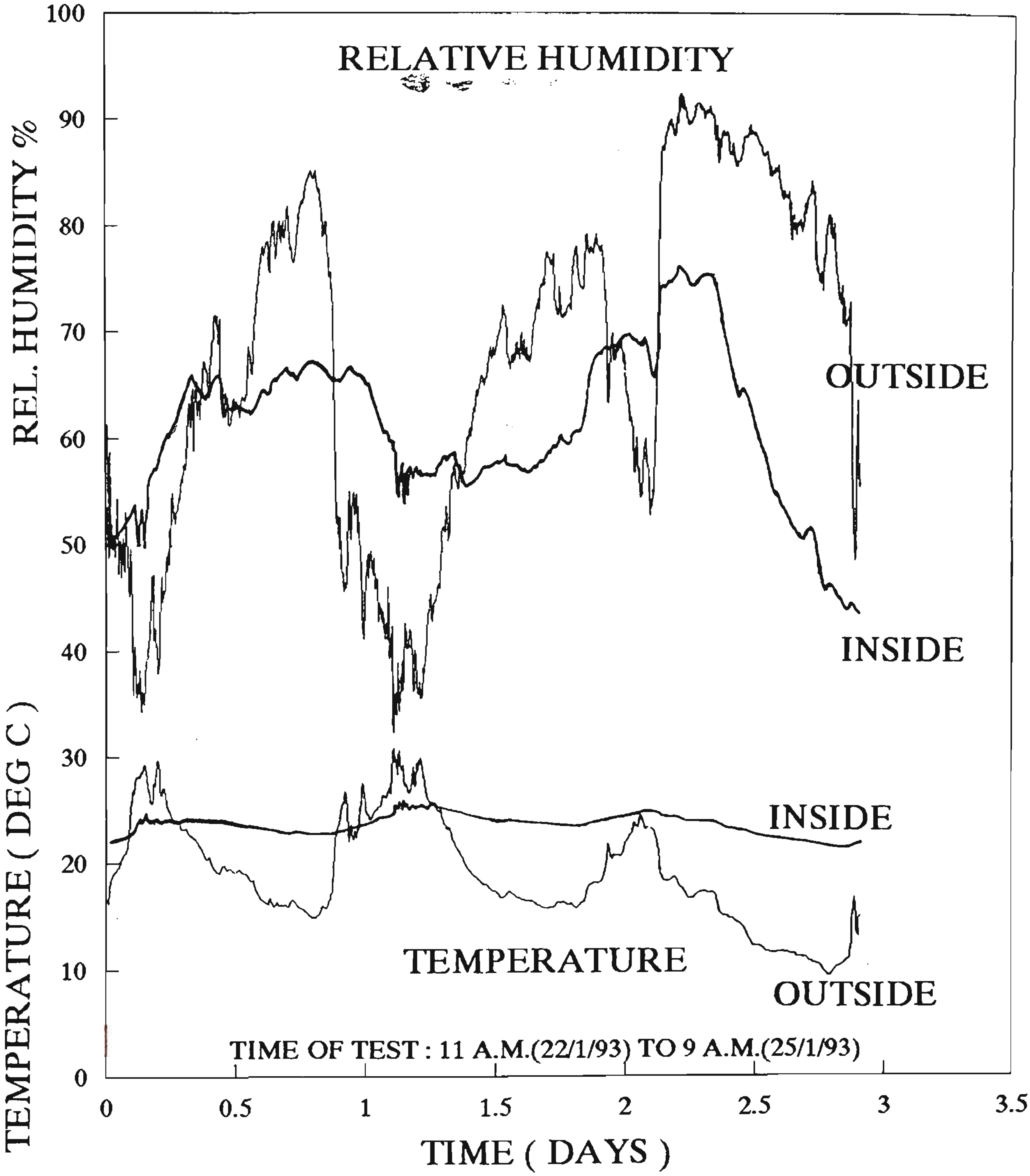


Figure 9. Humidity changes at Amcor warehouse
(Kirkpatrick, 1992)

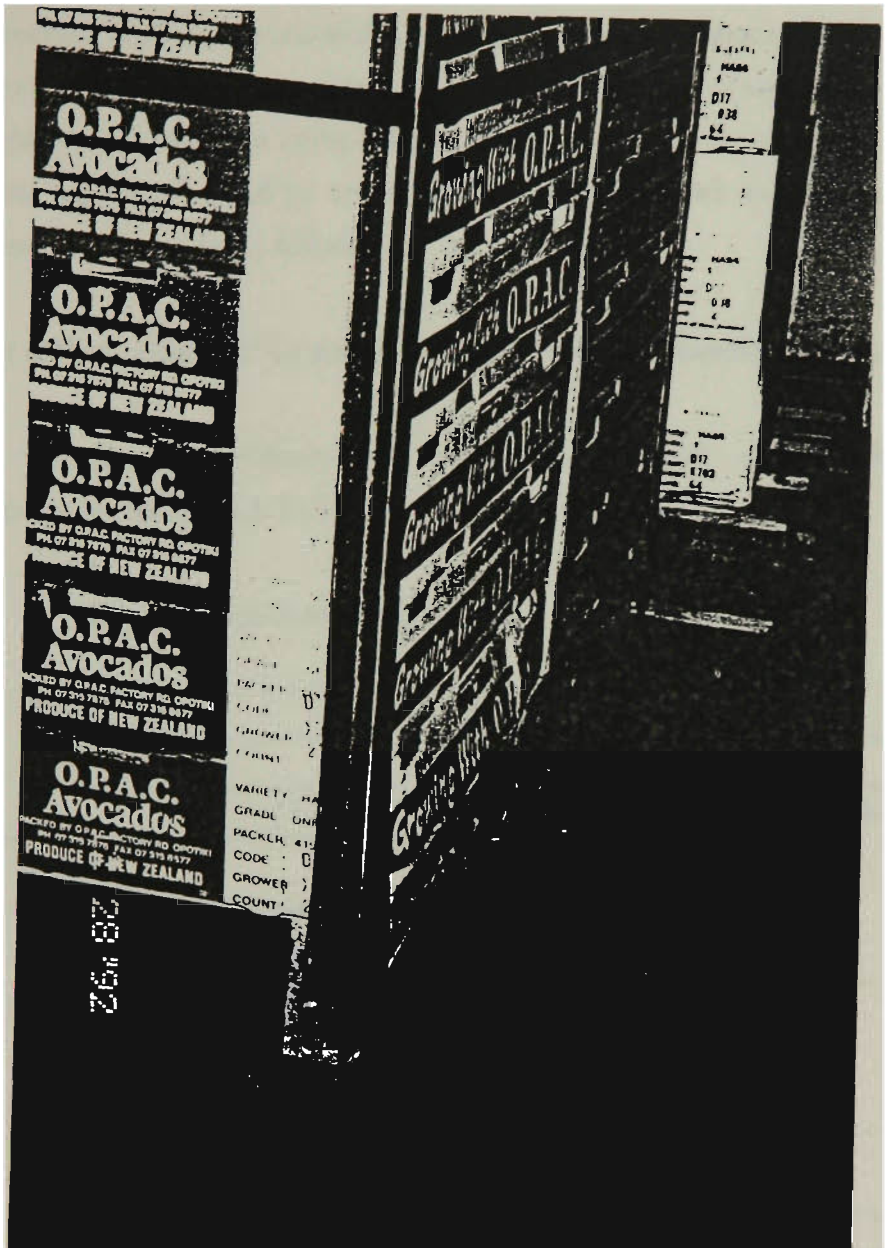


Figure 10. Example of boxes failed in air transport

4.0 EXPERIMENTAL DESIGN

To achieve the aims established for this study, experiments were designed to include the two most important tests for evaluating the top to bottom compression strength of corrugated fibreboard boxes: compression and creep tests. Compression tests were performed to determine the ultimate compression strength at a fixed deflection rate of 10 mm/min. Creep tests were performed by applying a percentage of the ultimate compression strength to determine the duration to failure.

4.1 Variables that affect compression strength of corrugated fibreboard boxes

Two factors were used to evaluate the compression strength: material and relative humidity. The different levels of each factor are shown in Table 1.

Table 1 Experimental design for compression test

		Factors	
		1	2
		Materials	Reletive Humidity
Levels	1	Virgin Boxes	50%
	2	Recycled Boxes	91%
	3	————	cyclic RH (91%-70%-91%)

Specifications of the boxes used are given in section 5.1. The levels of 50% and 91% RH were used because 50% RH is a standard condition and 91% RH is the highest relative humidity that the chamber can reach at Amcor; the cyclic RH was chosen between 70% and 91% because it not only represents the real humidity cycle in February in Darwin, but also meets the equipment availability at Amcor laboratory.

4.2 Variables that affect creep response of corrugated fibreboard boxes

Three factors were used to evaluate creep response: They are material, relative humidity and deadload. The deadload was defined as a percentage of compression strength of virgin boxes in the same test climate. The different levels of each factor are shown in Table 2.

Table 2 Experimental design for creep test

		Factors		
		1	2	3
		Materials	Relative Humidity	Dead Load
Levels	1	Virgin Boxes	91%	55%
	2	Recycled Boxes	cyclic RH (91%-70%-91%)	70%
	3	————	————	80%

4.3 Sample size

The Sample size was chosen according to the following formula, as suggested by Wheeler (1974).

$$n=(4r\sigma/\Delta)^2 \qquad (11)$$

Where: $r \geq 1$ = the number of levels of a factor

σ^2 = the variance of the observation

Δ = the minimum absolute pairwise difference between the expected values of the means of the r-level factor that one desires to detect with a α=0.05 level test and a power of β=0.90.

n = the total number of observations

For compression testing, pre-testing (ten samples of each box type) had shown that $\sigma \approx 180N$. Using $r = 3$, and $\Delta = 200N$ (4% of compression strength of virgin boxes) then: $n=(4\times3\times0.9)^2= 116.64 \approx 120$ (boxes)

For creep testing, pre-testing had shown that $\sigma \approx 0.9$ mm. Using $r = 3$ and $\Delta=1.25$ mm, (about 0.5% of the height of a box)
then: $n=(4\times3\times0.72)^2= 74.6 \approx 72$ (boxes)

For compression tests, 120 boxes were tested, 20 boxes for each treatment (each humidity and material). For creep test, 72 boxes were tested, 6 boxes for each treatment (each dead load, each material and 2 humidities: 91% and cyclic RH).

At a later stage in the experimental process, following further data analysis, it was decided to investigate the result at two lower deadload levels and proportional load levels (refer to Section 6.3).

5.0 EXPERIMENTAL PROCEDURES

5.1 Test Materials

RSC (Regular Slotted Containers) made of virgin and recycled materials, constructed of single wall C-flute corrugated board were used in the experiments. Pulp furnishes used in the components of the combined board are as follows:

- 210 g/m² Kraft Liner
  Mixture of Plantation Pinus Radiata Kraft pulp and N.S.S.C eucalypt

- 270 g/m² Test Liner
  Multiply sheet with the top ply a mixtures of Plantation Pinus Radiata and box makers waste and the back ply recycled fibre made from waste paper

- 181 g/m² Medium
  Mixture of Plantation Pines Radiata Kraft pulp and N.S.S.C. eucalypt

- 180 g/m² Medium
  Recycled fibre and size press starch

During the board making, recycled boards were treated with more starch than virgin materials to overcome some of the disadvantages of the recycled fibre. Addition of starch can strengthen fibre bonding and, hence, cause substantial improvement in strength such as ECT, tensile and tear resistance.

Moeller (1966) proposed that the adsorption of cationic starch creates new bonding sites on the fibre surface that are stronger than the original fibre to fibre bonds. In other words, the strength increase is due to additional fibre to fibre bonds and not to the strengthening of existing bonds. Fibres may adsorb, 4-5% cationic starch, the first 1-2% of which would be retained on the most active areas of the fibre surface, and thus the most likely potential bonding sites. Fibre to fibre bonding is usually explained by the formation of hydrogen bonds during drying. Hydrogen bonds are only effective over a very short distance, approximately 0.3 mm. Tough fibre surfaces have asperities larger than that, thus physically preventing the formation of hydrogen bonds. Addition of 1-2% cationic starch may fill out these asperities with an adhesive matrix, thereby creating new bonding areas as indicated earlier. Starch however, is in hydrophilic nature and moreover softens in high humidity environment.

Even though there were different chemical additives for the different boards, there is no significant difference in their ring crush values at standard conditions.

Initial tests were conducted on virgin and recycled linerboard and medium to determine the physical properties of the board components such as basis weight, thickness, and tensile values etc. Further tests were then conducted on virgin and recycled fibreboard to determine the physical characteristics of the board such as ECT and Stiffness values etc.

All materials and corrugated fibreboard boxes used in this study were supplied by APM (Australian Paper Manufactures Ltd). Table 3 shows the box specifications.

Table 3 Box specifications

	Virgin Box	Recycled box
Corrugation	C Flute	C Flute
Box Size (length×Width×Height)	406mm×306mm×236mm	406mm×306mm×236mm
Basic Weight Linerboard/Medium/Linerboard)g/m²	KLB210/FU181C/KLB210	CXL270/FS180/CXL270
Box Style	RSC	RSC

KLB -- Kraft Liner Board CXL -- Correx Liner Board

FU -- Semichemical medium FS -- Strong Fluting

5.2 Corrugator Trial

Four rolls of linerboard and 2 rolls of medium were passed separately through the board making machine.

Water resistant adhesives (Glue lines) control:

Corrugating consists essentially of flute formation and of gluing the flute tips to the facings. Adhesives used have basically been starch with some other additives such as resin to improve water resistant performance.

Failure of the glue bonds between corrugated medium and liners is a major factor in the collapse of corrugated containers under wet and humid conditions. McKee and Whitish (1972) observed that the boxes made with regular adhesive and regular components were more affected adversely by high humidity conditions than would be expected on the basis of box compression performance. At least in part, this outcome was due to adhesion failure under long-term loading at high levels of relative humidity.

It is therefore critical that a GBS (Glue Bond Strength) value be high so that problems such as failure only occurs on the paperboard, rather than at the glue line. The test of GBS provides a means of assessing the strength of the glue bonds in wet board and is also an important product control test for corrugated board which is intended for use in wet conditions. The adhesive used in this study was made with N.B. Love starch with a viscosity of 65 seconds at 23°C for the single facer glue and a viscosity of 17 seconds at 30°C the double facer glue, at the start of the trail.

GBS testing was performed according to Amcor Standard Method D4.178. Immediately after stage one (virgin fibreboard) was completed, a full deckle of corrugated board was taken from the corrugator and tested for GBS. For virgin fibre across the full deckle width the minimum level of GBS required had to be 140 N/m for the DF (double facer). For recycled fiber the GBS had to be 120N/m for the DF. When glue lines on the machine were cleared, the new batches from N.B. Love were run for 1 hour prior to start to allow adequate flushing of old starch.

<u>Paper Samples</u>

(a) Each reel had approximately 25mm stripped off outer layer and then 5 samples were cut from the reel. Each sample was 1000 mm length and as wide as the width of the reel.

(b) Each sample was placed on a template and labeled with direction, deckle position, operator and drive side, roll number, date, and stage. The samples were cut and stored between flat sheets of corrugated board for later property testing use.

An X=OP was marked on operator side of the reel. The end of samples were also marked with a corresponding X. In addition, SF or D BACKER were also marked to ensure orientation and position being correct.

After trial finished steps (a) and (b) were repeated.

<u>Sample Marking</u>

Each deckle position was colour coded right after the reels were mounted on the machine which is shown in Table 4.

Corrugator Speed

Corrugator speed was set at a value which gave good runnability of the 180 and 181 mediums. A speed of 130m/min at single facer and at double facer for all stages were used. After the process of preheating, gluing, cooling, slitting and scoring, and cutting off, the sheets of board were clearly marked, palletized and stored in a secure area, for later use in the box making sequence.

5.3 Box Making Trial

In order to ensure full water proofing of glue lines had been developed, boxes were made 10 days after the board blanks were taken off the corrugator.

Two stages with two positions of FC (Front Center) and BC (Back Center) from each stage were run at APM, Scoresby on a 2 Colour Summit 100 Box Maker with slots 6mm wide. Boxes were printed with only minimum identification such as P number, stage number and deckle position to avoid crushing damage.

The blank dimensions of boxes are shown in Figure 11.

After appropriate scoring, slotting, and gluing of manufacture's joint, boxes were completed. Those boxes were packed, palletized with shrink wraps and sent to the warehouse of Amcor Research and Technology Centre.

Table 4. Corrugator program

Stage No.	DF Liner	C Flute Medium	SF Liner	Colour Code (Single Facer) Boxes to be manufactured from Front Centre and Back Centre only: Scrap	Front Centre	Back Centre	Scrap	Corr. Speed (Approx) (m/min)	Glue	Blank Size (mm)	Box Style	Estimate Running Time (mins)	Est. No. of Blanks from each deckle position
1 Roll No.	KL210 49483-1B	FU181 4901-2B	KL210 49482-3B	472mm	Black	Green	472mm	130	W/proof	1480*553	RSC	4 mins 45 sec	400
2 Roll No.	KL270 28806-1B	FS180 42720-1B	KL270 28806-2B	472mm	Red	Orange	472mm	130	W/proof	1480*553	RSC	4 mins 45 sec	400

Note: SF–Single Facer
DF–Double Facer
All reel widths 2050mm and diameter 1530mm

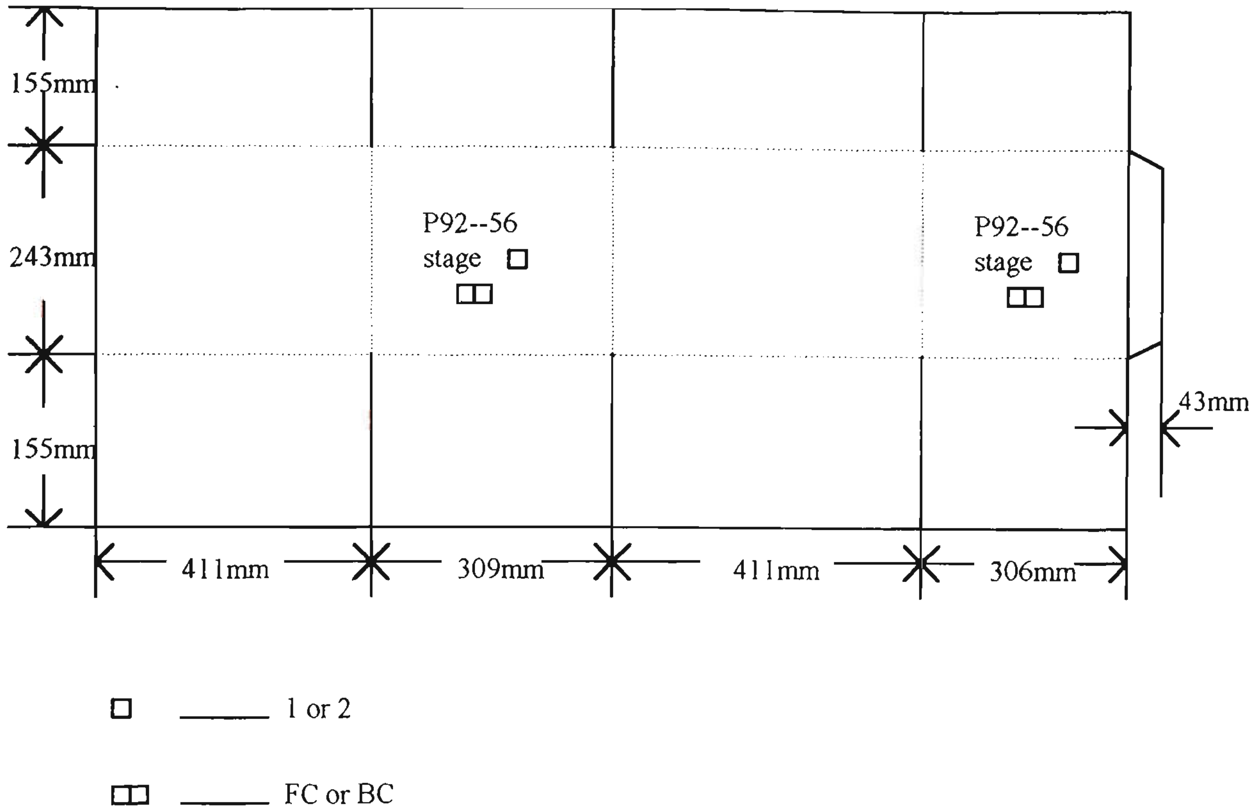


Figure 11. Blank and printing details

5.4 Box set up

Boxes with the manufacturer's joint attached by adhesive (Starch adhesive with wet strength resin added) were obtained from APM. Boxes were set up and sealed top and bottom with pressure sensitive tape with the 2/3 content inside to simulate the real products and to keep the boxes bulged at the same bow-out style. The contents used were plastic balls which have the diameters of 40mm.

5.5 Conditioning

Prior to conditioning all box samples at APPITA standard conditions, boxes were pre-conditioned at 25±2°C and 30±2% RH for at least two days. After this, they were transferred to a conditioning room kept at APPITA standard conditions of 25±1°C and 50±2% RH for at least 48 hours before testing. No time was allowed between conditioning and the beginning of tests, as this represents more realistically the distribution conditions. In industrial practice boxes are placed under load before they have time to reach moisture equilibrium. Using this procedure means that in the early stages at the testing the box materials were in an increasing moisture phase.

5.6 Test methods

Except for glue bond, MD shear, and creep, all other tests such as board component properties, board properties, and compression were conducted according to Australia Standards or APPITA Standards.

5.6.1. Board component property testing

Conditioning and testing of properties of board component were performed as shown in Table 5.

Table 5. Test standards for linerboard and medium

Property	Conditioned	Tested
Basis Weight	APPITA std condition	APPITA P405s-79
Thickness	APPITA std condition	AS1301.426s-88
MD. Tear	APPITA std condition	AS 1301.400s-91
CD Ring Crush	APPITA std condition	AS 1301.407s-88
Tensile	APPITA std condition	APPITA P 404s-81

5.6.2. Board properties testing

Conditioning and testing of corrugated fibreboard were performed as shown in Table 6.

Table 6. Test standards for board

Property	Conditioned	Tested
Grammage	APPITA std condition	APPITA P405s-79
Thickness	APPITA std condition	AS1301.426s-88
MD Shear	1). APPITA std condition 2). 23°C, 91% RH	Amcor D4.179-92
Edgewise Compression	1). APPITA std condition 2). 23°C, 91% RH	AS 1301.444s-88.
Hardness	APPITA std condition	AS 1301.445s-89.
Flat Crush	APPITA std condition	AS 1301.429s-89.
Liner Adhesion	1). APPITA std condition 2). 23°C, 91% RH	AS 1301.430s-89
Wet Strength Glue bond	APPITA std condition	Amcor D4.178.
Four Point Stiffness	1). APPITA std condition 2). 23°C, 91% RH	TAPPI T 820cm-85.

5.6.3. Box compression testing

The compression strength of the boxes were determined in accordance with APPITA 800s-87, using a fixed platen. The fixed platen was used because interests centred on the quality of box materials rather than the quality of box fabrication process.

Compression testing room was at the standard condition ($23 \pm 1^{\circ}$ C; $50 \pm 2\%$RH). For high humidity and cyclic RH testing, two boxes at a time were transported from the conditioning chamber to compression tester. The distance between the chamber and compression tester was 5 meters, which took less than 20 seconds to transport. Plastic bags were used to pack every box so as to avoid moisture content losses. According to standard, the preload used was 220N and the speed of platen was 10±3 mm/min. A load deflection curve was recorded as the test proceeded.

5.6.4. Creep testing

The experiment was designed in a way that minimized the environmental variation usually involved with creep testing. As described in section 4.3, a sample of virgin and recycled boxes was collected, and subjected to a series of tests under different dead loads and humidity levels in order to gauge their performance in real-life situations. Because of the size of the chamber, the tests were carried out on six boxes at a time. Thus for each environment regime, and at each deadload, three recycled boxes and three virgin boxes were tested simultaneously. The same procedure was repeated until a total of 180 boxes were tested.

5.6.4.1 Creep rigs

The creep rig consists of a frame, an upperplaten (fixed platen), a lowerplaten (floating platen), a load cell, a digital transducer, and four bellows (air cylinders), see Figure 12.

The boxes are placed between the platens. Air goes into four bellows to move up the floating platen until a given static load is applied. Loads are added by a pneumatic device and measured by a load cell which controls the pressure input via a computer in a closed loop control, to keep the load constant. The deflection is measured by transducer which was assembled under the lower platen. The computer records applied loads, creep deflections and stored pertinent information during testing. A sampling period of 4 seconds was used for the first 10 minutes, and a logging interval of 300s was used through the whole testing period.

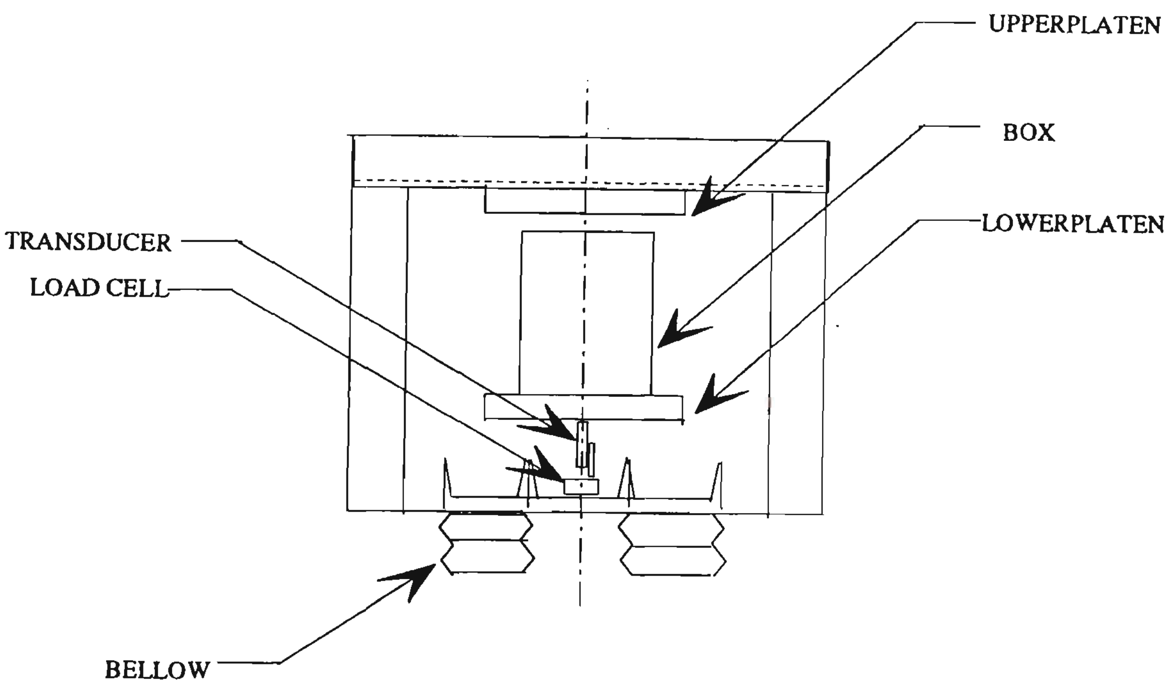


Figure 12. Creep rig

5.6.4.2 Box creep rigs calibration

A Phillips load cell was connected to a Phillips load readout unit and calibrated in an Instron universal tester. The load cell was used to calibrate the six new box creep rigs in the Tropical Room. The new linear displacement transducer was calibrated using a 40mm spacer block. It was repeatable over this distance to within 0.2 mm and accurate within 0.2 mm. The coil spring used in the Products Lab to check the Instron was placed in each of the new test rigs and the results were plotted. The results were compared to the Spring behavior in the Instron. The results of this testing were as follows:

- Deflection readings began at 250N and a final load of 1800 N was aimed at. At 25mm Spring deflection, the six new test rigs and the Instron had final loads ranging from 1781-1854 N, i.e., a 4% range. Among them, five of the six new test rigs had a final load within 22N, i.e., a 1% load range. This is considered an acceptable result.

- At 1800N Spring Load the deflections ranged from 24.35 to 25.57 mm, i.e., a 5% range.

- The 5% deflection range at 1800N load of the six new test rigs was considered acceptable for creep testing.

- The variations in spring stiffness were possibly due to slight differences in placement of spring centrally on floating platens of the test rigs.

- The close repeatability of the Spring test in the new test rigs showed that the new rigs should give close comparative test results.

5.6.4.3 Environmental control

Temperature and humidity of the chamber were controlled by a computer program. In the program, the set points of humidity and temperature were input. When humidity went lower than the set point , the chessel 390 controller would receive a signal from the RH Sensor and then control the air solenoid valve to turn the spray on or control the water bath/heater to raise humidity. When humidity went over the set point, the chessel controller would stop raising humidity and also control the cooling coils to drop humidity.

For temperature control, the chessel pulsed heaters/cooling coils on a ratio basis using a RID(Proportional, Integral, Derivative) algorithm. For example 100% control output meant 100% heat and 0% cool. The temperature and humidity of the chamber were measured by thermometer and hygrometer, which were calibrated by wet and dry bulb named "ASSMAN".

5.6.5. Moisture content determination

The moisture content was determined on every two boxes tested for compression strength immediately after compression testing, and on four samples of each trial for creep test. The top flaps of those boxes were cut into about 150mm×50mm samples and the moisture content was determined in accordance with P 401s-78.

5.7 Test Sequence

The testing sequence is shown in Figure 13.

Compression Testing:

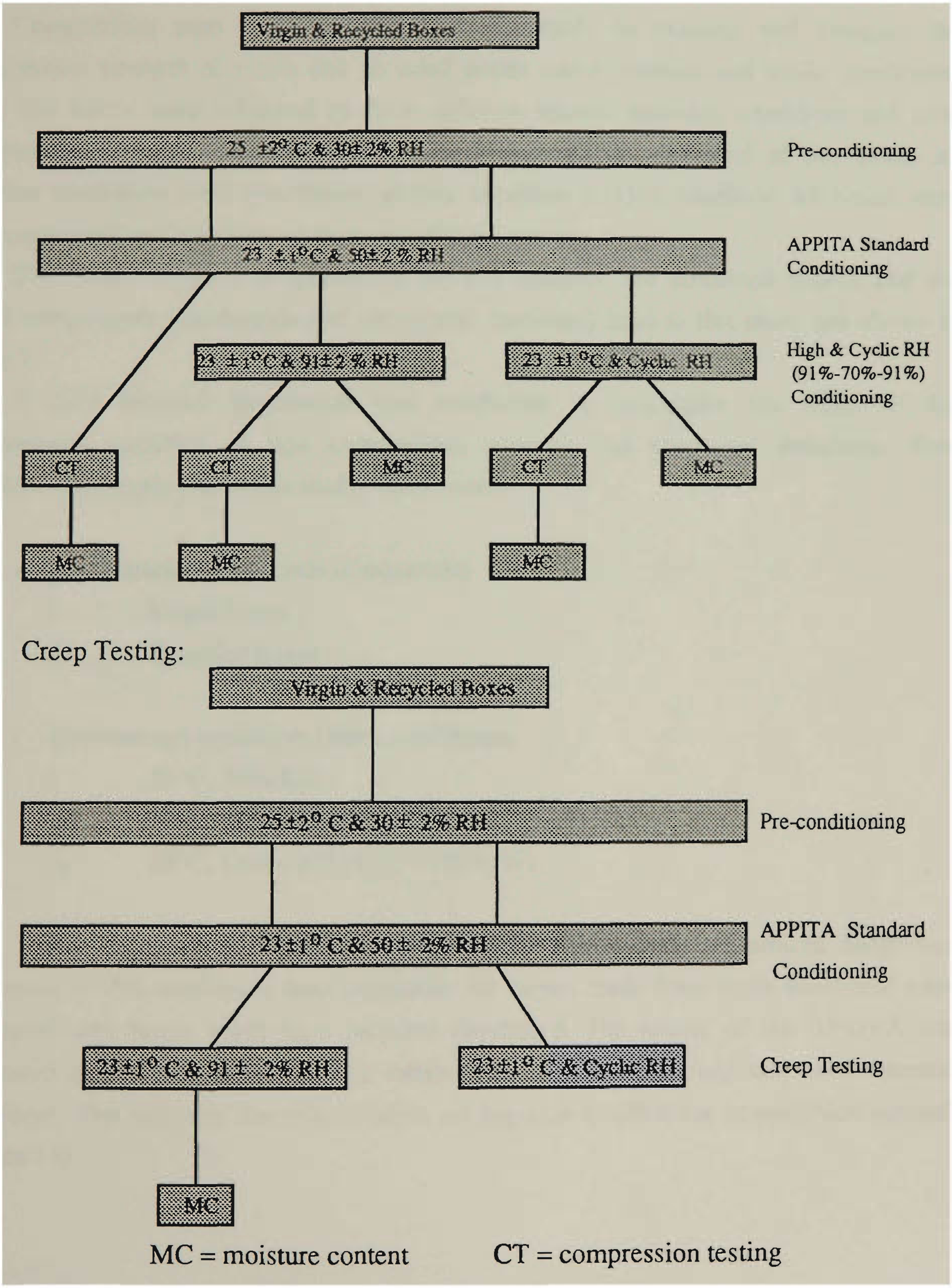


Figure 13. Test sequence

6. RESULTS AND DISCUSSION

6.1. Compression strength

Compression tests were completed in this study to examine and compare the compression strength of virgin and recycled boxes under constant and cyclic conditions. Over 120 boxes were subjected to three different relative humidity conditions and their compression strength evaluated. The moisture contents of each kind of box under all different conditions were determined. Before exposure to each condition, all boxes were pre-conditioned and conditioned in the conditioning room.

The "basic" physical properties of the box samples, the combined boards and the board components (linerboards and corrugated mediums) used in this study are shown in Table 7.

A 2×3 factorial experiment was conducted to investigate the effect of the experimental variables on box compression strength and maximum deflection. Two variables were evaluated in this study. These were:

- Box materials (two kinds of materials)
  - i. Virgin boxes
  - ii. Recycled boxes

- Environment conditions (three conditions)
  - i. 23°C, 50% RH
  - ii. 23°C, 91% RH
  - iii. 23°C, Cyclic RH (91%-70%-91%)

A 2-way analysis of variance (ANOVA) for a completely randomized design was performed at 95% confidence level (Appendix A). Boxes made from virgin fibreboard were compared with boxes made from recycled fibreboard. The results of the ANOVA test suggested that there were two way interactions between materials and environmental conditions. This indicates that two variables act together to affect the compression strength (Figure 14).

Table 7. Physical properties of the box materials

(a). Paper property testing summary

DESCRIPTION			CXL210	210KLB	FS180C	FU181C
GRAMMAGE (g/m2)			262	206	181	177
THICKNESS (mm)			0.39	0.33	0.31	0.31
MD. TEAR (mN)			2761	2761	1296	1780
CD RING CRUSH (N)			440	450	401	422
TENSILE	MD	STRENGTH(kN/m)	17.9	17.3	11.2	13.9
		STRETCH(%)	1.56	1.40	1.77	1.54
		WORK (J/m2)	182	152	131	137
		EXT. STIFFNESS (kN/m)	2245	2140	1339	1686
	CD	STRENGTH(kN/m)	5.86	7.10	4.90	6.78
		STRETCH(%)	3.15	3.93	2.73	3.03
		WORK (J/m2)	139	210	101	150
		EXT. STIFFNESS(kN/m)	679	801	629	793

(b). Board property testing summary

DESCRIPTION		VIRGIN BOARD	RECYCLED BOARD
GRAMMAGE			
S/F(g/m2)		205	259
D/F(g/m2)	(S/H)	202	256
Medium(g/m2)		252	243
Total Grammage (g/m2)		670	790
THICKNESS (mm)	(S/H)	4.24	4.35
MD. SHEAR (kN/m)	(S/H)	26.7	26.7
	(H/H)	10.2	7.5
	Retention (%)	38%	28%
EDGEWISE COMPRESSION (kN/m)	(S/H)	9.37	9.86
	(H/H)	4.28	3.60
	Retention (%)	46%	37%
HARDNESS (kPa)	(S/H)	160	148
FLAT CRUSH (kPa)	(S/H)	201	174
PIN ADHESION (kN/m)	(S/H)	0.90	0.94
	(H/H)	0.53	0.54
	Retention (%)	59%	57%
3 POINT STIFFNESS (BENDING)	(S/H) MD	13.0	13.6
	CD	6.40	5.06
	(H/H) MD	5.50	4.08
(Nm)	CD	1.75	1.28
	Retention (%) MD	43%	30%
	Retention (%) CD	27%	25%
4 POINT STIFFNESS (BENDING)	(S/H) MD	17.5	19.8
	CD	8.16	7.16
	(H/H) MD	10.7	8.6
(Nm)	CD	3.82	2.52
	Retention (%) MD	61%	44%
	Retention (%) CD	47%	35%
GLUE BOND STRENGTH	S/F (N/m)	100	110
	D/F (N/m)	140	120

Note: 1. An average of 10 test samples

2. See Appendix B for 3&4 point stiffness test summary for more details

3. S/H: Standard humidity (23'C,50% RH)

H/H: High humidity (23'C, 91% RH)

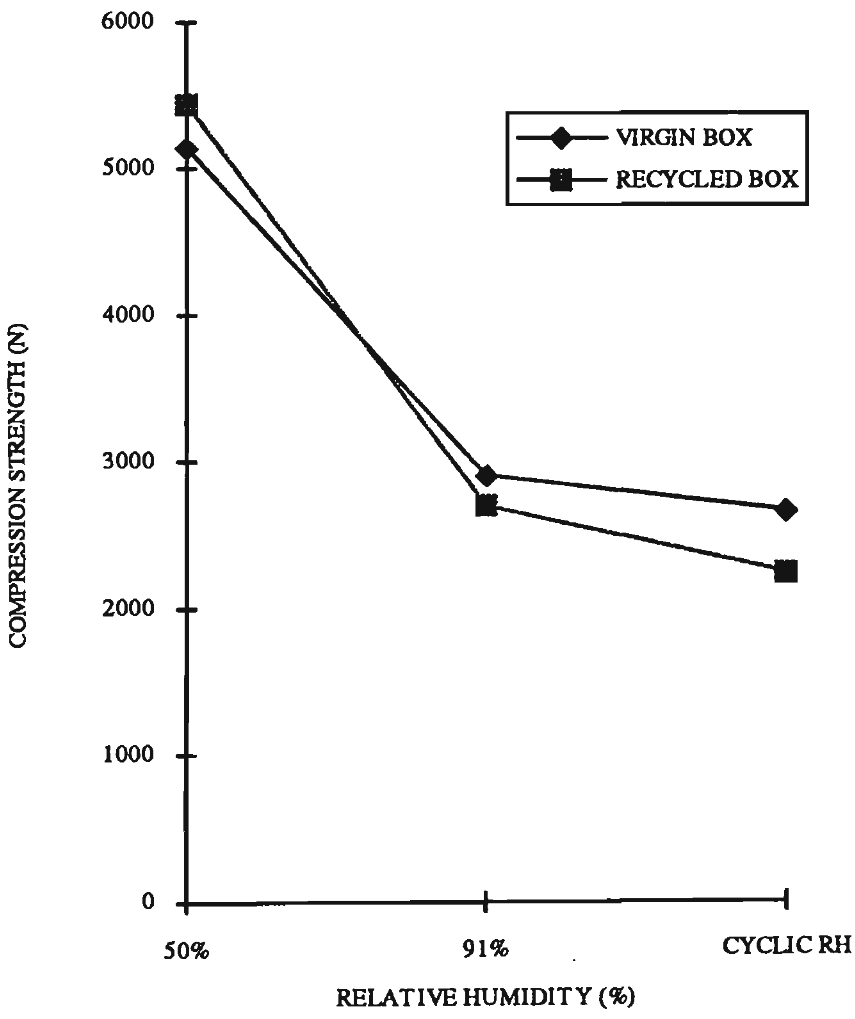


Figure 14 Graph of a 2×3 interaction for compression strength

6.1.1. Virgin boxes versus recycled boxes

In this study, the examinations of the differences in loss of strength due to the humidity changes, and comparisons of the final compression strength after exposure to constant and cyclic RH conditions were conducted to compare the potential stacking performance of virgin and recycled boxes.

6.1.1.1 Loss of strength

The average compression values for each group of boxes are summarized in Table 8. A graphical presentation is shown in Figure 15. Corrugated board is a highly variable material. The fabrication process of containers from this material further increased the variances. Measurements performed in this research had a large standard deviation. This variation in data obscures any trends that may be seen by just looking at the raw data. For this reason statistical analysis must be performed on the data to see if there are significant differences occurring.

On the basis of t-test analysis, the initial compression strength of boxes held at APPITA standard condition was significantly different between the two box types at 99.9% confidence level (Appendix C). Recycled boxes were 297 N (approximately 5.8%) higher in compression strength than virgin boxes, after conditioned at 23C°, 50% RH. The average box compression strength loss due to constant 91% RH and cyclic condition was compared using a t-test analysis (Appendix D). The results from the analysis are shown in Table 9. At a confidence level of 99.9%, significant differences between two box types were found under both 91% RH and cyclic RH. Recycled boxes experienced significantly greater loss of strength than virgin box. The loss of strength for each box type is shown in Table 9. A graphical presentation of the loss of strength is shown in Figure 16.

The fibreboard used in recycled boxes was 2.6% thicker and has an 18% higher grammage than fibreboard used in virgin boxes. Thus, as expected, results showed that recycled boxes have higher compression strength than virgin boxes at APPITA standard condition. Virgin boxes had higher compression strength than recycled boxes after conditioning at 23°C, 91% and cyclic RH (91%-70%-91%). This affect is presumed to occur because there was more starch in the board used to make recycled boxes than virgin boxes. Recycled board was treated with starch to overcome some of the disadvantages of the recycled fibre. Addition of starch can strengthen fibre bonding and, hence, cause substantial improvement in strength such as ECT, tensile and tear resistance at standard conditions.

Table 8. Box compression strength

		LOAD (N)	STD. DEVIATION
VIRGIN BOARD	(S/H)	5143	151
	(H/H)	2905	174
	(C/H)	2664	137
RECYCLED BOARD	(S/H)	5440	173
	(H/H)	2700	76
	(C/H)	2242	172

Note: 1. An average of 20 test samples, and see Appendix E and F for more details
2. S/H: Standard humidity (23'C,50%)
H/H: High humidity (23'C, 91%)
C/H: Cyclic RH (91%-0%-91%)

Table 9. Difference in loss of strength between virgin and recycled boxes

Condition	T-Test value	Prob>|T|	Loss of Strength (N) Virgin Box	Recycled Box
91% RH	7.53	0.0000	2238	2740
Cyclic RH	10.18	0.0000	2479	3198

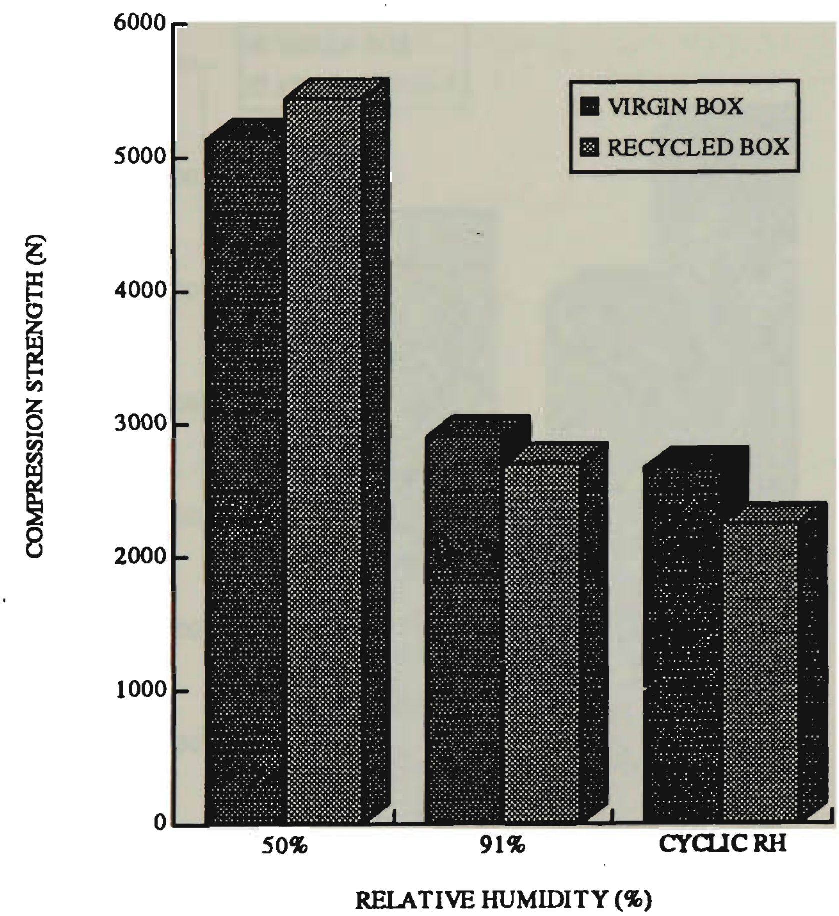


Figure 15. Compression strength
(Averages for virgin and recycled boxes)

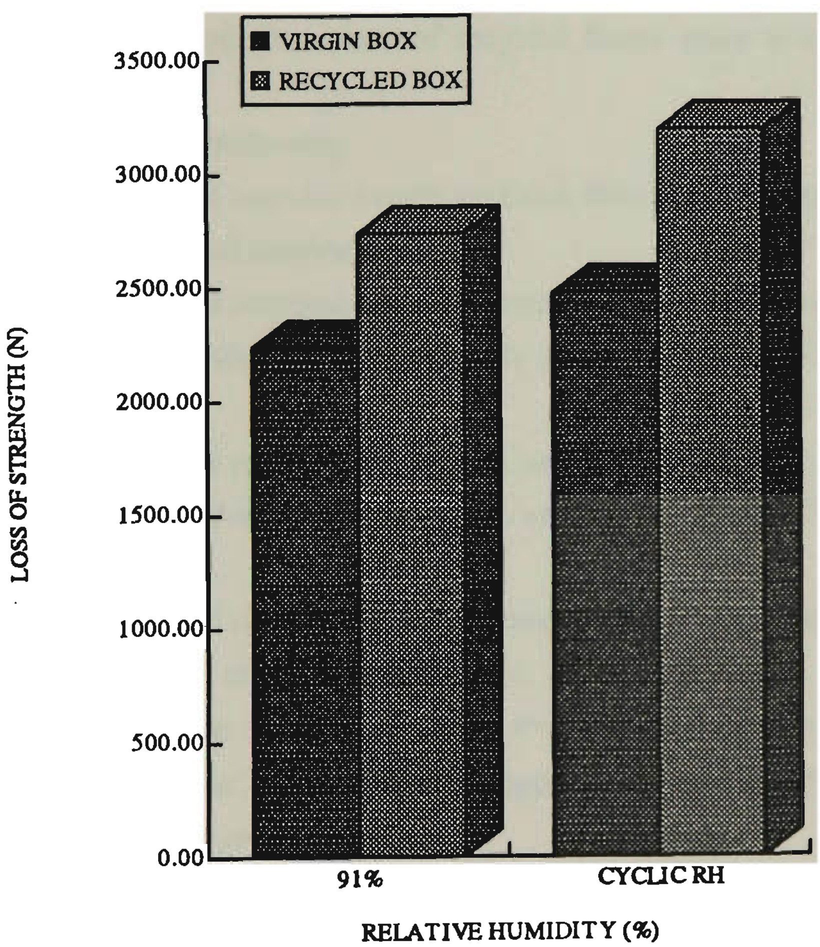


Figure 16. Difference in loss of strength between virgin and recycled boxes

The starch however is hydrophilic in nature. In high humidity environment, it will react with moisture. This explains why BCT values for virgin boxes are higher than recycled boxes at conditions more severe than at APPITA standard.

6.1.1.2 Final compression strength

Box compression strength is closely related to ECT values and stiffness of boards. Table 10 shows the test values for ECT, stiffness of boards and compression strength of boxes. From Table 10, it can be seen that all of the values at high humidity were lower than that in standard humidity and the values of recycled boxes were even lower than virgin boxes.

Key results include the following:

- At high RH virgin and recycled boards retained 46% and 37% respectively of their ECT values at standard conditions.
- At high RH virgin and recycled boards retained 42% and 30% respectively of their three point stiffness values in MD; and 27% and 25% of that in CD at standard conditions.
- At high RH virgin and recycled boards retained 61% and 43% respectively of their four point stiffness values in MD; and 47% and 35% of that in CD at standard conditions.
- At high RH virgin and recycled boxes retained 57% and 50% respectively of their compression strength at standard conditions.

We note in passing that Mckee's formula ($P=5.78P_m(HZ)^{1/2}$), based on component properties would predict box compression strength values some 10% lower than these actual compression strength test values.

The average values with their standard deviations (σ) of compression strength for virgin and recycled boxes under three different levels are shown in Figure 17.

Final box compression strength after exposure to 91% RH and cyclic RH were compared between virgin and recycled boxes using a t-test analysis (Appendix G). At a confidence limit of 99.9%, significant differences were found under both 91% and cyclic RH conditions. The results from the analysis are shown in Table 11. The final compression strength of virgin box was 205 N (7.6%) and 422 N (18.8%) higher than recycled box under 91% and cyclic RH respectively.

This results thus suggest that these two kinds of boxes will not perform equally under the high humidity and cyclic humidity conditions used in this study. Therefore, for 91% RH, a safety factor of 1.8 for virgin boxes and 2.0 for recycled boxes should be used, for cyclic

RH a safety factor of 1.9 for virgin boxes and 2.4 for recycled boxes should be applied to the test or predicted values at standard conditions.

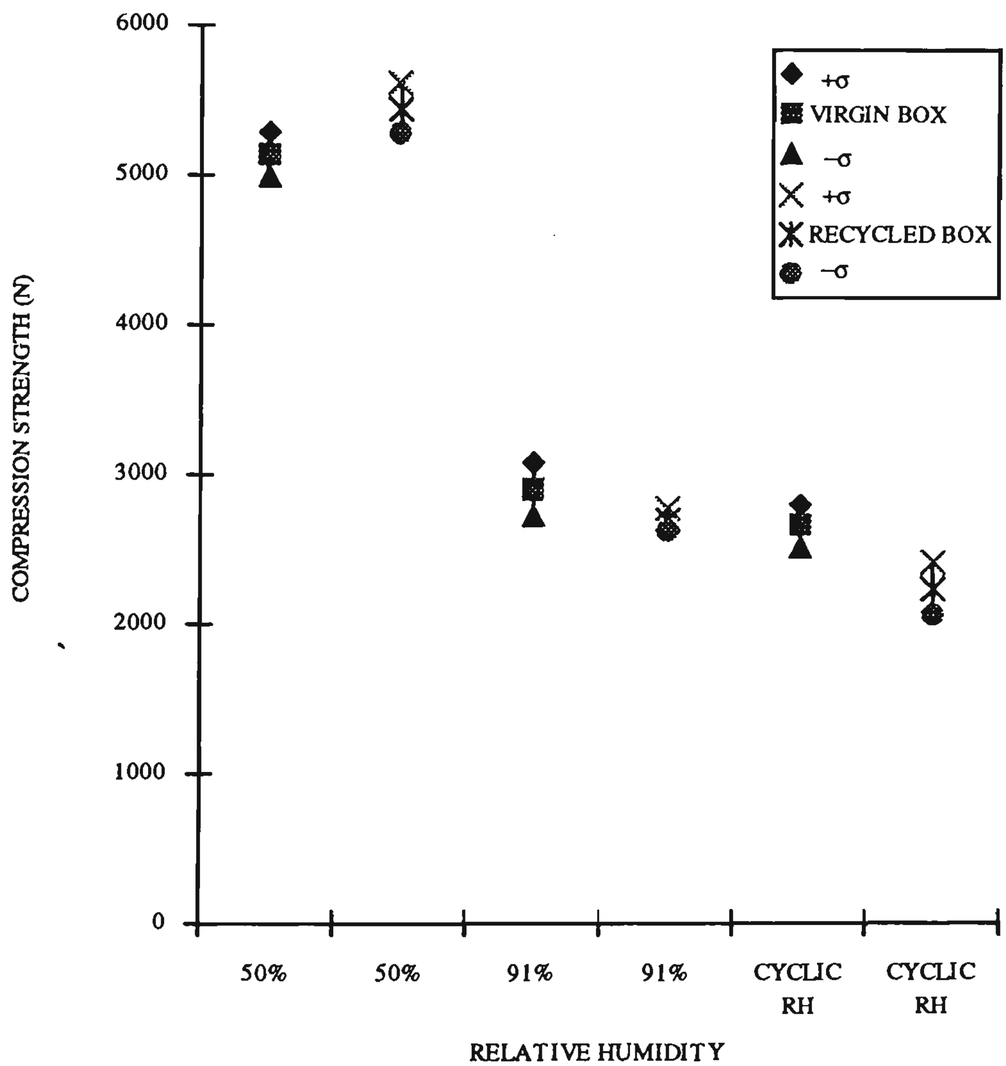


Figure 17. Compression strength
(Averages for virgin and recycled boxes with their standard deviations (σ))

Table 10. Test results for ECT, stiffness, and box compression strength

Mat'l	Condition	ECT KN/m	Stiffness Nm				Box compression Strength N
			MD	CD	MD	CD	
Virgin Boxes	SH	9.37	12.96	6.4	17.49	8.16	5143
	HH	4.28	5.5	1.75	10.68	3.82	2905
Recycled Boxes	SH	9.86	13.59	5.06	19.8	7.16	5440
	HH	3.6	4.08	1.28	8.62	2.52	2700

Table 11. Difference in final compression strength between virgin and recycled boxes under 91% and cyclic RH conditions

Condition	T-Test value	Prob>|T|	Difference in Final Compression strength (N)
91% RH	-4.81	0.0001	205
Cyclic RH	-8.57	0.0000	422

6.2 Effect of moisture history and cyclic condition

Cellulosic materials respond to changes 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 fibreboard box.

To determine the significance of the cyclic condition on compression strength of recycled and virgin boxes, two t-tests were used to compare the box compression strength under 91% and cyclic RH conditions. At the 99.9% confident level, a significant difference of compression strength was found between boxes conditioned at 91% RH and cyclic RH for both box types (Appendix H). The boxes conditioned at 91% RH had higher compression strength than those conditioned at cyclic RH, even though the moisture contents of boxes were not significantly different at 99% confidence level (Appendix I) when retrieved from the chamber (both 91% and cyclic RH).

The cyclic condition caused significant reduction in compression strength for both box types. The reduction in compression strength due to exposure to the cyclic conditions for each box type is shown in Table 12.

One can argue that this occurs because of a phenomenon called ageing. Ageing has been well documented for synthetic polymers, but has apparently been overlooked for paper. Padanyi (1992) suggested that mechano-sorptive effects and physical ageing/de-ageing are actually the same phenomenon and exist in paper for both moisture absorption and desorption. Ageing represents the movement of an amorphous structure towards thermodynamic equilibrium below its glass-transition temperature, and is reversible. The phenomenon of ageing is a general affect, largely independent of the molecular structure, qualitatively well described by reduction in free volume and molecular mobility, and increase in relaxation times.

In this case, when boxes had been conditioned at 91% RH for three days, the boxes had been aged for three days. During this process, free volume and molecular mobility were reduced, its strength therefore was increased. When boxes were conditioned in cyclic RH for three days however, they experienced a substantial continuous de-ageing process, or inhibition of ageing, maintaining a far-from-equilibrium state and this led to a low compression strength.

These results show clearly that compression strength of a box is not only related to final moisture level of the box, but also related to the history of a box gaining the moisture. Moisture equilibrium alone will not be sufficient for adequate testing for some mechanical properties, such as compression strength.

Table 12. Loss of compression strength for each box type after exposure to cyclic condition comparing with exposure to 91% RH

Mat'l	Compression Strength (N)		*Loss of Compression Strength	
	91% RH	Cyclic RH	(N)	(%)
Virgin boxes	2904	2664	240	8.3
Recycled Boxes	2700	2242	458	17

*Average of 20 samples of each material
Std deviation of tests given in Table 8.

6.3 Creep Response

Creep tests were completed to examine and compare the creep response of virgin and recycled boxes under constant and cyclic conditions. Over 180 boxes were subjected to two different relative humidity conditions and more than three different deadloads. Their responses were then evaluated. The moisture contents of each kind of box under high humidity conditions were determined. Before exposure to creep test environment, all boxes were pre-conditioned at 25±2°C, 30±2% RH and conditioned at 23±1°C, 50±2% RH in the conditioning room.

A 2×2×3 factorial experiment was conducted to investigate the effects of the experimental conditions on box creep responses. Three variables were evaluated in this study. These were:

- Box types (two box types)
  - i. Virgin boxes
  - ii. Recycled boxes

- Environment conditions (two conditions)
  - i. 23°C, 91% RH
  - ii. 23°C, Cyclic RH (91%-70%-91%)

- Deadloads (three deadloads)
  - i. 55% of compression strength of virgin boxes[1]
  - ii. 70% of compression strength of virgin boxes
  - iii. 80% of compression strength of virgin boxes

Apart from deadloads mentioned above, low loads (33% and 40% of compression strength of virgin boxes at 23°C, 91% RH) have also been done for both box types at 91% RH, so that we could obtain more points to predict survival life of boxes at the similar conditions.

In addition, two other series of tests were performed:

---

[1] Based on mean values of compression strength of virgin boxes at 23°C, 91% RH and 23°C, cyclic RH conditions respectively

(1) Recycled boxes were subjected to deadloads calculated as percentage (33%, 40%, 55%, 70%, 80%) of compression strength of recycled boxes at high condition (23°C, 91% RH) and,

(2) Recycled boxes were subjected to deadloads calculated as 70% and 80% of compression strength of recycled boxes under cyclic condition.

Finally, 33% of maximum compression strength of virgin boxes at 23°C, 91% RH was applied to both box types at 23°C, cyclic RH to verify the effect of cyclic RH on the creep performance of the boxes.

A 3-way analysis of variance (ANOVA) for a completely randomized design was performed at 99.9% confidence (Appendix J). Boxes made from virgin fibreboard were compared with boxes made from recycled fibreboard. The results of the ANOVA test suggested that there were two way interactions between materials and environmental conditions. This indicates that two variables act together to affect the creep rates of boxes. In addition, there was a three-way interaction among all three factors in creep rate (materials, environment conditions and deadloads). This indicated that the three factors act together to affect the creep rate.

6.3.1 Moisture sorption rate of virgin and recycled boxes

Cellulosic materials absorb and desorb moisture at different rates under relative humidity environments. This affects the performance of a corrugated fibreboard box.

In order to better understanding the cause of creep rate acceleration, the moisture gain during high humidity has been investigated.

The result in this study indicates that recycled boxes have lower absorption rate than virgin boxes (Figure 18). This lower moisture rate in recycled boxes is probably due to the irreversible humification effects of drying in the fabrication process.

Byrd (1984) concluded from his study that increased creep rates resulted from increased moisture sorption by fibreboard.

A lower absorbtion rate is presumed to cause a low creep rate, and in turn, a longer survival time of boxes.

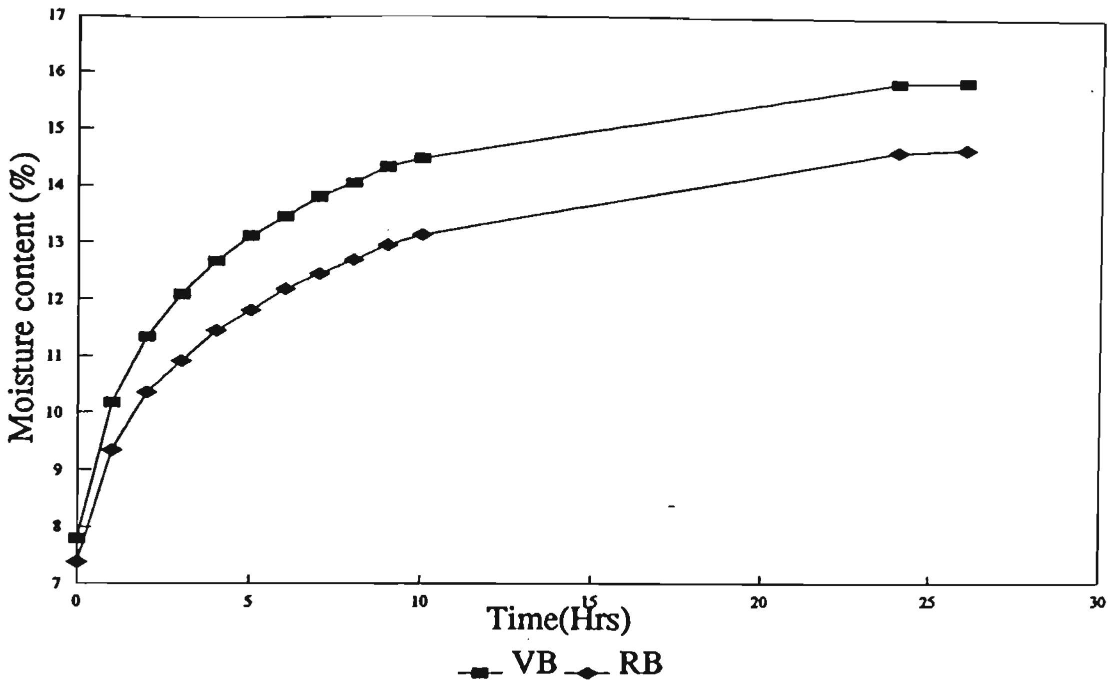


Figure 18. Moisture content vs. time

6.3.2 Virgin boxes versus recycled boxes under high constant and cyclic relative humidity.

In this section, comparisons of final creep strain, stacking life and final secondary creep rate after high and cyclic RH exposure were conducted to compare the potential stacking performance of the two box types. Prediction of survival time has also been determined by the means of load versus survival time and creep rate versus survival time. Table 13 presents the test values of final deflection, strain, stacking life and creep rate for both virgin and recycled boxes subjected to various deadload at 91% and cyclic RH.

6.3.2.1 Relation of final creep strain to time

The behavior of the corrugated fibreboard boxes made from both virgin and recycled fibreboards subjected to various deadloads and two relative humidity conditions appeared to follow a general pattern that was reported by previous researchers (Moody and Skidmore, 1966). Figures 19a and 19b show the strain as a function of time as measured during compressive creep tests in a high constant and cyclic humidity environment under different deadloads. Zero deflection was set at the preload of 250N. The different colours used in Figure 19 represent individual replicates.

Apparently the primary region takes from a few minutes to 30 hours for virgin boxes and from a few minutes to 5 hours for recycled boxes. The secondary region showed a uniform but much slower rate. Because of the linear relationship between creep and time, creep rate was calculated as the slope of the line. In the tertiary region, failures occurred, including buckling and crushing of all four panels. The typical box failure showed four panels bowed out. The maximum bulge was 35.6% of width (width increased from 306mm to 415 mm) for virgin boxes, and 22.5% (306mm to 375 mm) for recycled boxes. Bulge was measured from the center of the panel along the length of the box.

Box creep strains after exposure to high and cyclic RH conditions were compared between boxes made from virgin and recycled fibreboards using the t-test analysis under various deadloads (Appendix K). The results from the analysis are shown in Table 14. At a confidence level of 95%, a significant difference in strain was found only under 1661N deadload which is 40% of the compression strength of the virgin boxes at 91% RH. The strain of virgin boxes is 0.12 mm/mm higher than recycled boxes. Under the rest deadloads, the strains are not significantly different.

This result that most of the strains were not significantly different under various deadloads differs from the results for strains obtained from BCT testing. In the latter, the differences of deflections (creep strains) are significant between two box types at both 91% RH and cyclic RH.

This is because in the compression test the load was applied after the boxes had been conditioned for 48 hours in the testing regime, hence the board moisture content had stabilized prior to the test. In the creep test, the loads were applied without previous conditioning to the actual testing regime, and the moisture content of the boxes is still changing during the first 24 hours of the test (Figure 18). The fact that, under testing, moisture changes were still occurring after the test had started has probably confounded any differences between the two type of boxes.

Another reason for this is the statistical technique used. Due to the fact that we used a sample size of 72 boxes in creep testing, 6 replicates of each treatment, the detectable difference between two groups of means will be 1.25 mm (0.0053 mm/mm for strain). Hence any difference smaller than 1.25 mm (0.0053 mm/mm) was not detected.

This test result suggests that, when the deadload is above 1161N at 91% RH and 1465N at cyclic RH, the performances of strains of the two types of boxes are similar.

Table 13.

Responses of boxes subjected to various deadloads at different humidity levels

Responses of boxes subjected to various deadloads at 91% RH

	(1)&(2)	(3)	(4)	(5)&(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
	33%			40%			55%			70%			80%		
	VB	RB	RB	VB	RB	RB	VB	RB	RB	VB	RB	RB	VB	RB	RB
	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH
	958N	958N	890N	1161N	1161N	1079N	1596N	1596N	1483N	2032N	2032N	1888N	2322N	2322N	2158N
Final Deflection (mm)	NF	11.4	10.8	11.2	9.9	10.4	11.6	11.6	11.1	12.3	9.9	10.0	11.8	11.9	11.2
	10.7	11.4	12.7	11.6	9.8	10.4	9.2	10.4	11.1	9.9	10.1	9.4	9.0	10.1	8.6
	13.7	10.6	11.8	10.6	10.8	10.9	11.3	11.7	12.5	12.5	11.4	10.3	10.5	11.3	10.7
	NF	11.1	----	11.4	10.5	12.3	9.9	11.8	11.0	10.6	11.6	11.6	12.7	11.3	11.2
	NF	9.7	----	10.1	10.2	----	11.1	9.4	11.2	9.2	10.0	10.0	9.4	10.9	12.7
	NF	11.2	----	11.1	9.8	----	11.3	11.1	11.7	11.3	11.7	11.3	11.0	11.3	11.6
	NF			11.4											
	NF			11.6											
	NF			11.6											
				NF											
MEDIAN	----	11.2	11.8	11.4	10.0	10.4	11.2	11.3	11.2	11.0	10.8	10.2	10.8	11.3	11.2
AVG	----	10.9	11.8	11.2	10.1	11.0	10.7	11.0	11.4	11.0	10.8	10.4	10.7	11.1	11.0
STDS	----	0.66	0.96	0.52	0.44	0.87	0.95	0.91	0.58	1.31	0.83	0.8	1.4	0.6	1.4
Final Strain (%) (mm/mm)	NF	4.82	4.57	4.75	4.18	4.42	4.90	4.90	4.70	5.20	4.20	4.23	5.00	5.03	4.75
	4.53	4.83	5.38	4.90	4.13	4.42	3.90	4.40	4.70	4.20	4.30	4.00	3.80	4.30	3.65
	5.80	4.50	5.00	4.47	4.59	4.61	4.80	4.95	5.30	5.30	4.81	4.38	4.45	4.80	4.55
	NF	4.69	----	4.81	4.45	5.20	4.20	4.98	4.65	4.50	4.90	4.90	5.40	4.80	4.75
	NF	4.11	----	4.27	4.31	----	4.70	4.00	4.75	3.90	4.25	4.22	4.00	4.60	5.40
	NF	4.76	----	4.72	4.13	----	4.80	4.70	4.95	4.80	4.95	4.80	4.68	4.80	4.90
	NF			4.48											
	NF			4.93											
	NF			4.93											
				NF											
MEDIAN	----	4.73	5.00	4.75	4.25	4.42	4.75	4.80	4.72	4.65	4.56	4.31	4.57	4.80	4.75
AVG	----	4.62	4.98	4.70	4.30	4.66	4.55	4.66	4.84	4.65	4.57	4.42	4.56	4.72	4.67
STDS	----	0.28	0.41	0.24	0.19	0.37	0.40	0.39	0.25	0.55	0.35	0.35	0.60	0.25	0.58

Note: VB ---- Virgin Box
RB ---- Recycled Box
NF ---- Not Failed
---- ---- Missing points
CSVH ---- Compression Strength of Virgin boxes at High (91%) humidity
CSREH ---- Compression Strength of Recycled boxes at High (91%) humidity

Responses of Boxes Subjected to Various Deadloads At 91% RH

	(1)&(2)	(3)	(4)	(5)&(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
	33%			40%			55%			70%			80%		
	VB	RB	RB	VB	RB	RB	VB	RB	RB	VB	RB	RB	VB	RB	RB
	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH	CSVH	CSVH	CSREH
	958N	958N	890N	1161N	1161N	1079N	1596N	1596N	1483N	2032N	2032N	1888N	2322N	2322N	2158N
Survival Time(Hr)	*103.8	24.3	30.2	18.9	17.3	10.6	3.75	3.74	4.77	1.50	1.58	2.00	0.49	1.00	1.24
	56.1	29.0	44.8	20.7	12.7	19.4	2.92	3.25	3.91	1.17	1.17	1.75	0.58	0.58	0.67
	68.2	15.9	70.2	14.3	14.3	11.7	2.60	3.48	4.08	1.24	1.66	1.83	0.49	1.00	0.99
	*233.7	20.4	----	16.9	14.4	47.7	2.48	3.83	5.34	1.33	1.82	2.42	0.75	0.80	1.41
	*73.2	13.3	----	8.0	10.7	----	3.14	3.16	4.25	1.25	1.43	1.58	0.50	0.50	1.24
	*452.6	19.2	----	11.7	14.9	----	3.40	3.33	3.55	1.00	2.08	1.91	0.66	0.80	1.32
	*476.8			10.2											
	*129.2			34.0											
	*413.7			20.0											
				*59.0											
MEDIAN	129.2	19.8	44.8	19.5	14.3	15.5	3.03	3.41	4.17	1.25	1.62	1.87	0.54	0.80	1.24
AVG	223.0	20.3	48.4	21.4	14.0	22.3	3.05	3.47	4.32	1.25	1.62	1.92	0.58	0.78	1.15
STDS	177.1	5.66	20.2	15.1	2.20	17.3	0.48	0.27	0.64	0.17	0.31	0.29	0.11	0.21	0.27
Creep Rate mm/mm/hr10^{6}	52.0	980	670	810	1200	1930	3800	5100	3700	10200	9300	7600	37300	19800	12800
	240.9	860	600	800	1450	1140	4500	5700	5100	13900	13300	9800	37700	29200	26600
	335.0	1280	280	1190	1380	1400	5100	5600	4400	12700	11300	8700	51500	15300	16000
	30.3	1130	----	1070	1420	390	7200	5100	3600	9700	9600	8300	35700	19800	11300
	42.9	1900	----	2170	1900	----	5800	6100	5000	11300	11100	10200	47100	39200	12500
	34.3	1200	----	1500	1240	----	5500	6100	5100	23900	7500	8200	31600	20300	13200
	22.6			1520											
	45.7			410											
	36.1			790											
				280											
MEDIAN	51.6	1165	440	940	1400	1270	5300	5650	4700	12000	10350	8500	37500	20050	13000
AVG	93.3	1225	517	1054	1432	1215	5317	5617	4483	13617	10350	8800	40150	23933	15400
STDS	113.2	364	208	566	250	641	1169	449	697	5273	1998	1002	7539	8749	5703

Note: VB ---- Virgin Box
RB ---- Recycled Box
NF ---- Not Failed
---- ---- Missing points
CSVH ---- Compression Strength of Virgin boxes at High (91%) humidity
CSREH ---- Compression Strength of Recycled boxes at High (91%) humidity
* ---- Failure time predicted

Responses of boxes subjected to various deadloads at different humidity levels (Cont)

Responses of boxes subjected to various deadloads at cyclic (91%-70%-91%) RH

	(18)	(19)	(20)&(21)	(22)&(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
	33%		33%		55%		70%			80%		
	VB	RB	VB	RB	VB	RB	VB	RB	RB	VB	RB	RB
	CSVH	CSVH	CSVC	CSRC	CSVC	CSVC	CSVC	CSVC	CSRC	CSVC	CSVC	CSRC
	958N	958N	879N	735N	1465N	1465N	1865N	1865N	1559N	2131N	2131N	1872N
Final Deflection (mm)	NF		NF		9.2	9.0	9.4	11.2	9.4	10.9	11.2	10.9
					8.3	9.9	10.8	11.2	9.5	11.6	10.1	9.9
					9.9	8.0	11.5	11.2	8.3	11.3	10.6	10.9
					9.2	9.0	13.1	9.9	9.9	11.1	11.8	10.8
					9.2	9.0	11.2	----	11.4	11.8	8.4	12.2
					10.5	9.0	----	----	9.2	10.0	10.2	----
MEDIAN					9.2	9.0	11.2	11.2	9.5	11.2	10.4	10.9
AVG					9.4	9.0	11.2	10.9	9.6	11.1	10.4	10.9
STDS					0.7	0.6	1.3	0.6	1.0	0.6	1.1	0.8
Final Strain (%) (mm/mm)	NF		NF		3.90	3.82	3.97	4.76	4.00	4.60	4.75	4.61
					3.50	4.20	4.57	4.74	4.03	4.91	4.30	4.20
					4.20	3.40	4.86	4.74	3.50	4.78	4.50	4.60
					3.90	3.82	5.55	4.20	4.20	4.72	4.98	4.58
					3.90	3.82	4.74	----	4.82	4.98	3.57	5.18
					4.43	3.82	----	----	3.90	4.25	4.32	----
MEDIAN					3.90	3.82	4.74	4.74	4.02	4.75	4.41	4.60
AVG					3.97	3.81	4.74	4.61	4.08	4.71	4.40	4.63
STDS					0.32	0.25	0.57	0.27	0.43	0.26	0.48	0.35

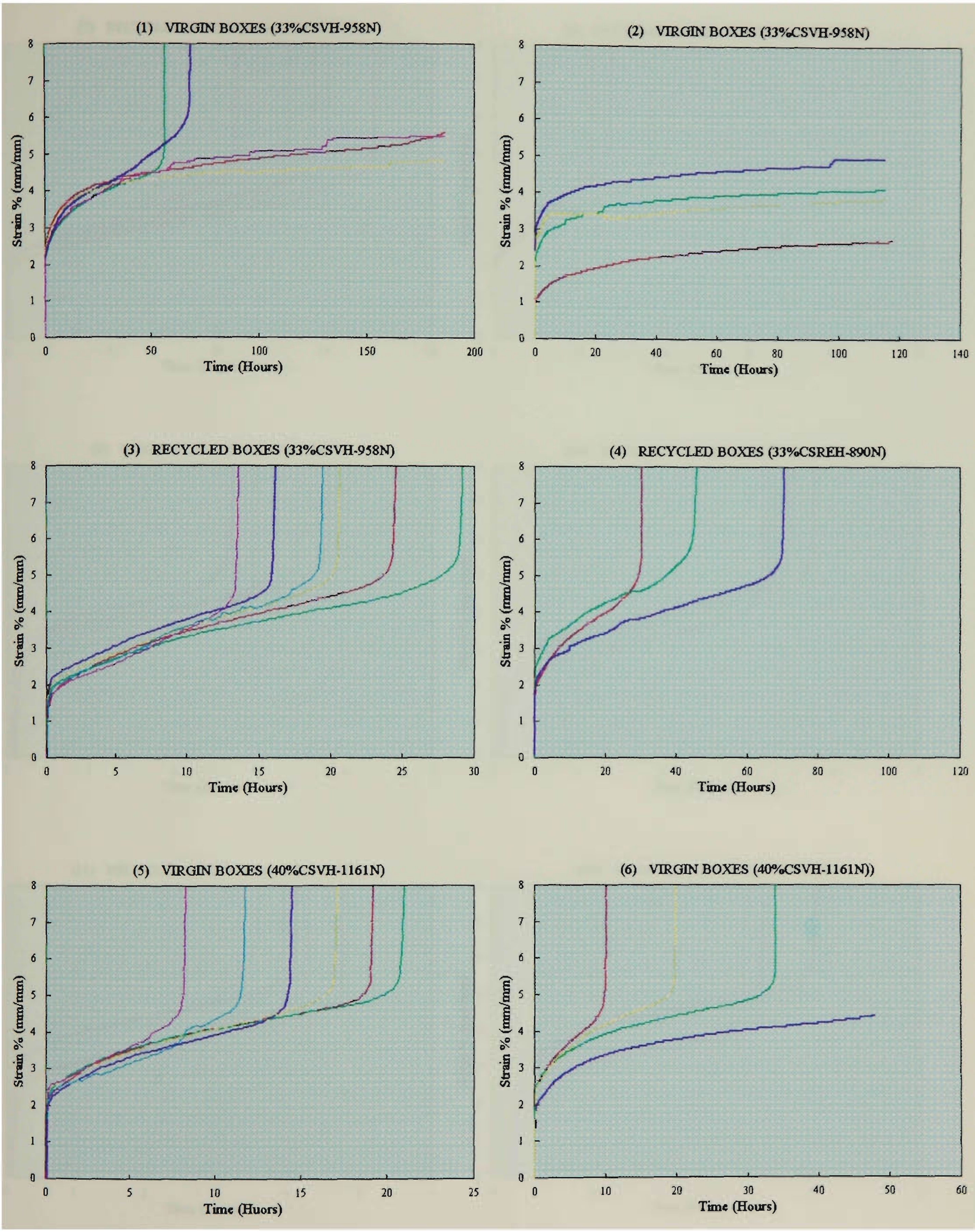
Note: VB ---- Virgin Box
RB ---- Recycled Box
NF ---- Not failed
---- ---- Missing points
CSVC ---- Compression Strength of Virgin boxes at Cyclic (91%-70%-91%) humidity
CSRC ---- Compression Strength of Recycled boxes at Cyclic (91%-70%-91%) humidity

Responses of boxes subjected to various deadloads at different humidity levels (Cont)

Responses of Boxes Subjected to Various Deadloads At Cyclic (91%-70%-91%) RH

	(18)	(19)	(20)&(21)	(22)&(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)
	33%		33%		55%		70%			80%		
	VB	RB	VB	RB	VB	RB	VB	RB	RB	VB	RB	RB
	CSVH	CSVH	CSVC	CSRC	CSVC	CSVC	CSVC	CSVC	CSRC	CSVC	CSVC	CSRC
	958N	958N	879N	735N	1465N	1465N	1865N	1865N	1559N	2131N	2131N	1872N
	*530.2	*138.9	*196.7	*323.7	22.0	22.5	1.3	15.2	17.8	0.9	1.5	15.5
	*240.4	*198.6	*286.0	*176.1	22.6	17.4	15.8	16.1	15.9	1.7	0.9	1.9
	*421.8	*205.5	*197.0	*336.6	22.8	22.4	2.4	16.1	17.3	0.8	1.2	14.0
	*325.2	*108.6	*750.1	*218.6	23.8	21.1	14.8	17.3	18.5	1.0	1.6	2.8
Survival	*142.0	*195.4	*515.6	67.87	20.0	19.4	1.5	----	15.4	1.7	0.9	14.0
Time(Hr)	*263.3	*251.1	*355.7	*131.8	21.7	20.2	----	----	18.6	0.7	1.7	----
			*534.6	*712.2								
			*599.6	*208.4								
			*686.4	*732.1								
MEDIAN	294.3	197.0	515.6	218.6	22.3	20.7	2.4	16.1	17.5	0.9	1.4	14.0
AVG	320.5	183.0	458.0	323.0	22.1	20.5	7.1	16.2	17.2	1.1	1.3	9.6
STDS	138.4	51.0	207.1	241.4	1.3	1.9	7.5	0.8	1.3	0.5	0.3	6.7
	17.9	149.1	56.7	82.6	80.0	120.0	10170	190	130	11690	10900	220
	31.2	87.8	54.9	140.5	110.0	170.0	120	200	190	11690	15980	7950
	24.1	109.6	77.6	86.6	90.0	80.0	6650	120	120	17290	15980	350
Creep Rate	37.9	221.5	16.7	75.0	80.0	140.0	270	120	170	13730	15110	6520
mm/mm/hr10^6	136.7	109.1	16.6	433.6	90.0	170.0	7120	----	250	13220	15250	280
	45.1	88.0	22.5	25.2	120.0	80.0	----	----	160	16780	10020	----
			14.5	20.0								
			17.9	76.5								
			14.4	20.0								
MEDIAN	34.5	109.4	17.9	76.5	90.0	130.0	6650	155	165	13475	15180	350
AVG	48.8	127.5	32.4	106.7	95.0	126.7	4866	158	170	14067	13873	3064
STDS	44.1	51.2	23.9	128.7	16.4	40.8	4473	43	47	2445	2683	3841

Note: VB ---- Virgin Box
RB ---- Recycled Box
NF ---- Not Failed
---- ---- Missing points
CSVC ---- Compression Strength of Virgin boxes at Cyclic (91%-70%-91%) humidity
CSRC ---- Compression Strength of Recycled boxes at Cyclic (91%-70%-91%) humidity
* ---- Failure time predicted



Note: CSVH----Compression Strength of Virgin boxes at High (91%) humidity

CSREH----Compression Strength of Recycled boxes at High (91%) humidity

Figure 19 a. Strain as a function of time (23°C, 91% RH)

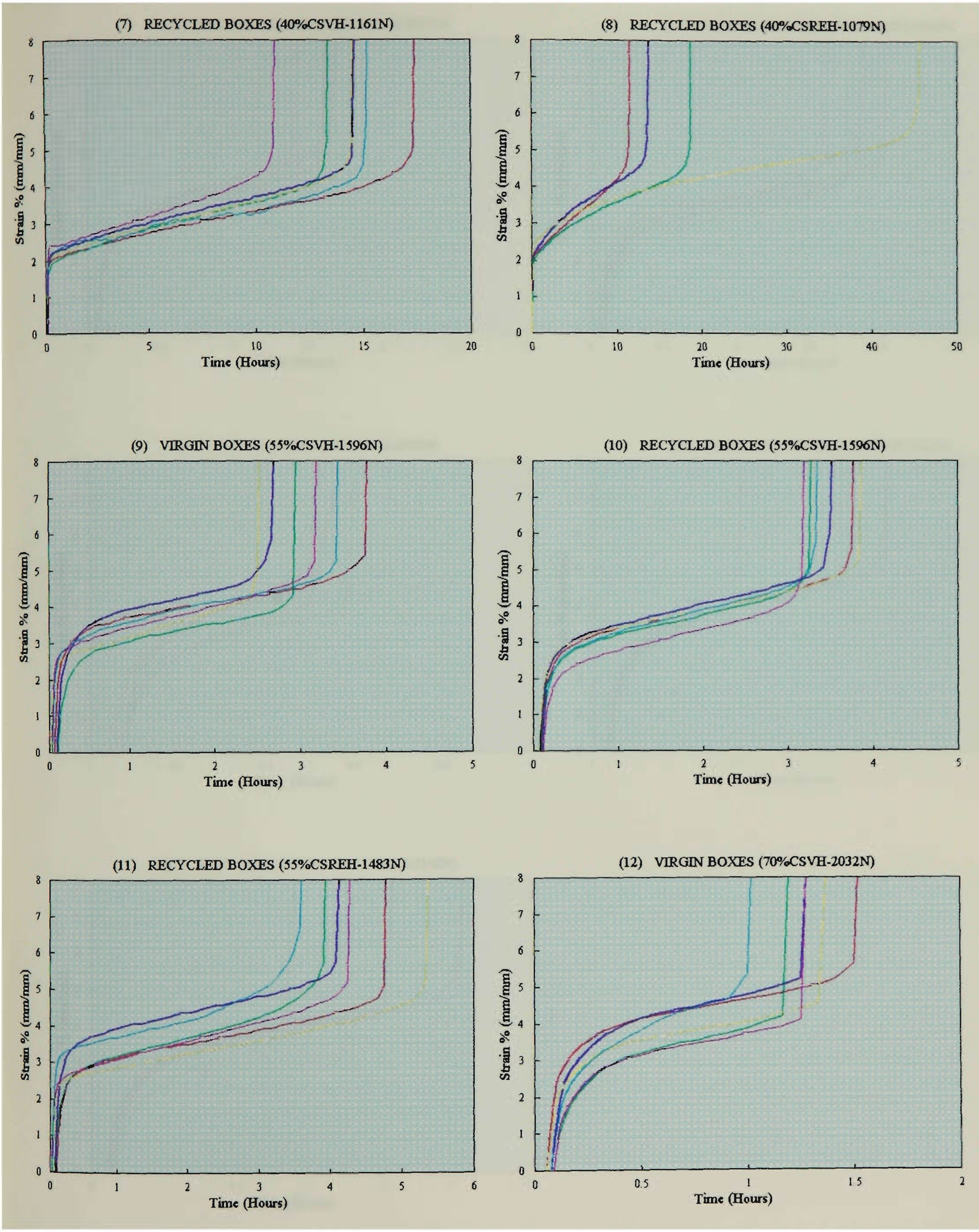


Figure 19a. Strain as a function of time -- 23°C, 91% RH (cont)

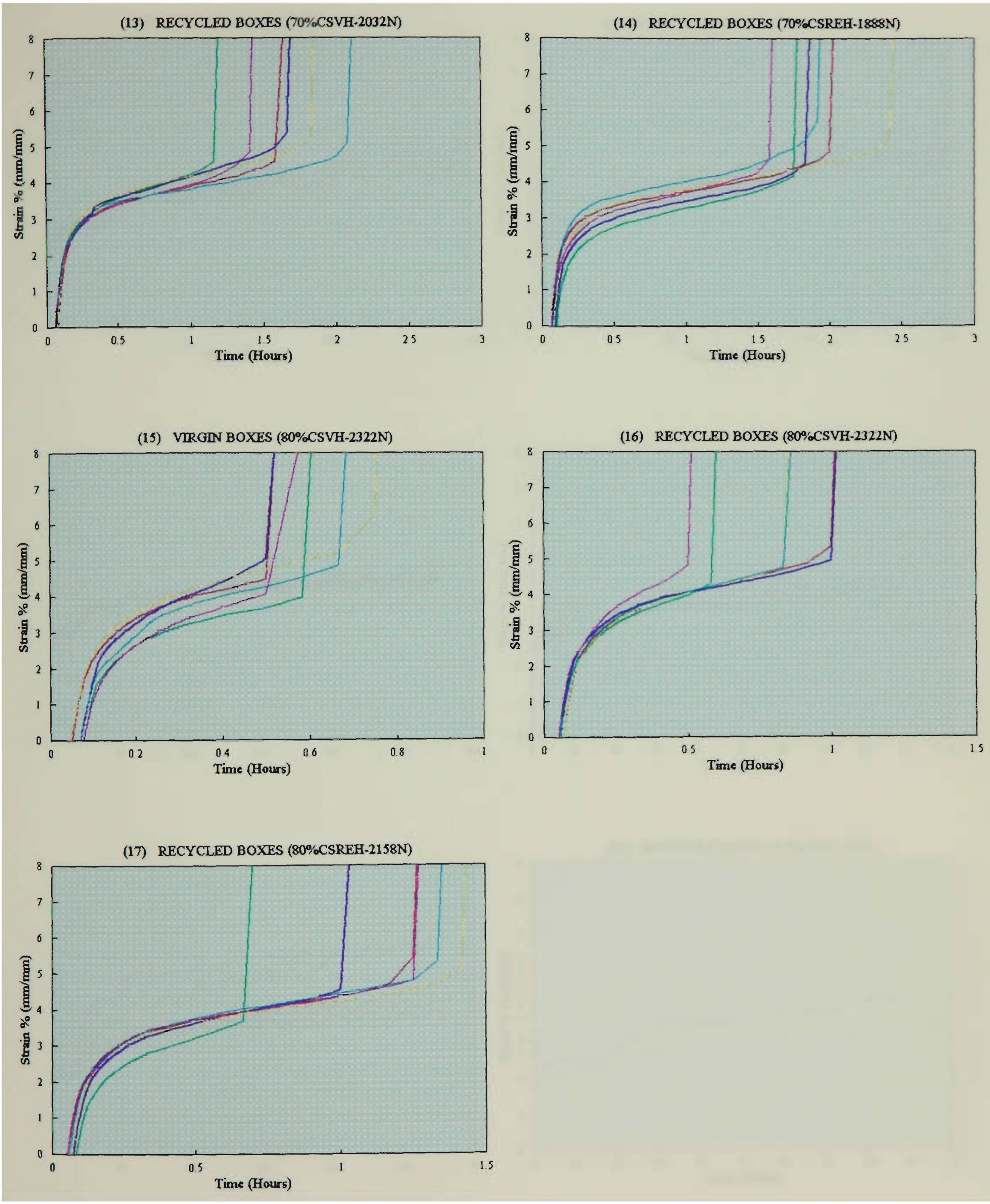
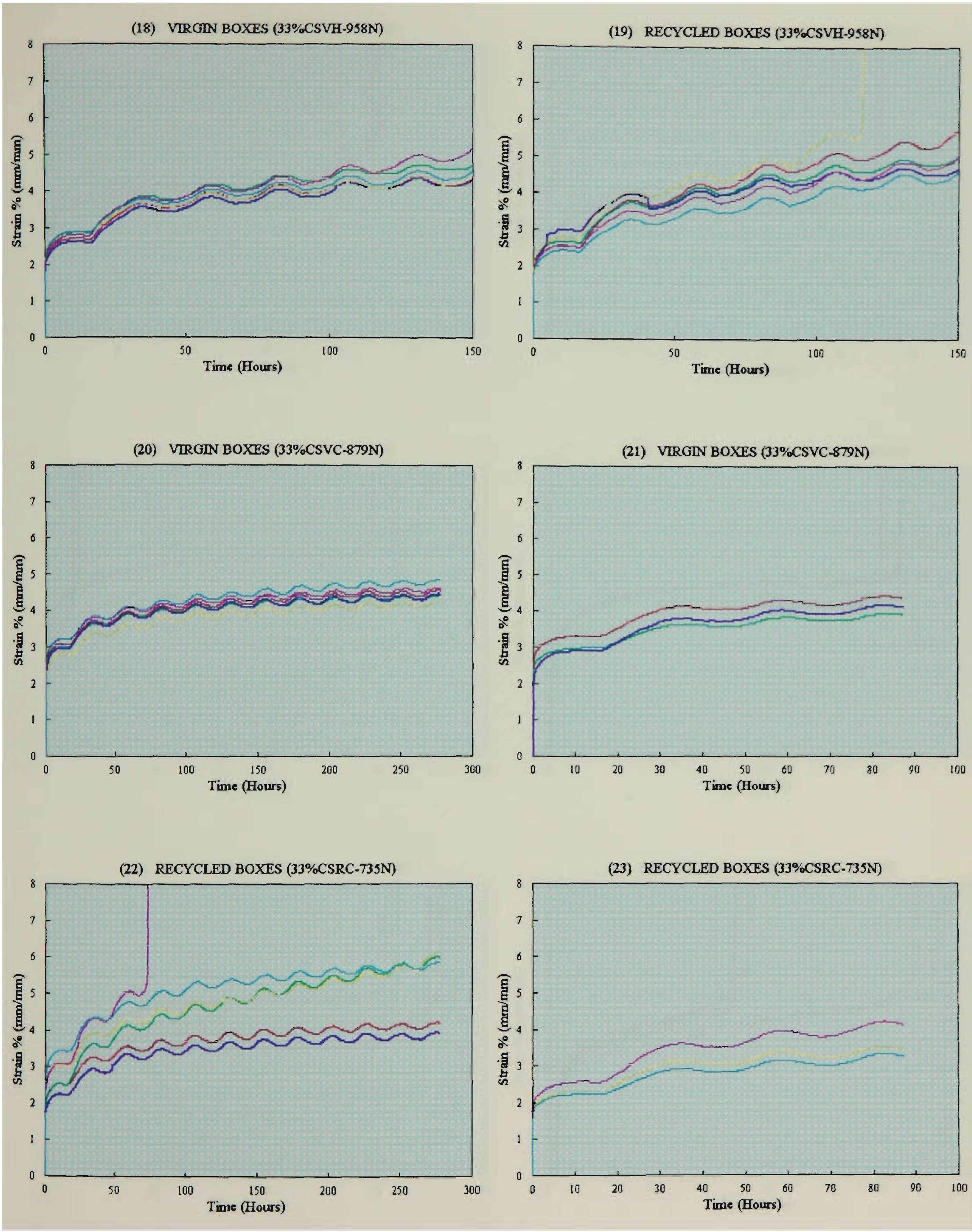


Figure 19a. Strain as a function of time -- 23°C 91% RH (cont)



Note: CSVH----Compression Strength of Virgin boxes at High (91%) humidity
CSVC----Compression Strength of Virgin boxes at Cyclic (91%-70%-91%) humidity
CSRC----Compression Strength of Recycled boxes at Cyclic (91%-70%-91%) humidity

Figure 19b. Strain as a function of time -- 23°C, Cyclic (91%-70%-91%) RH

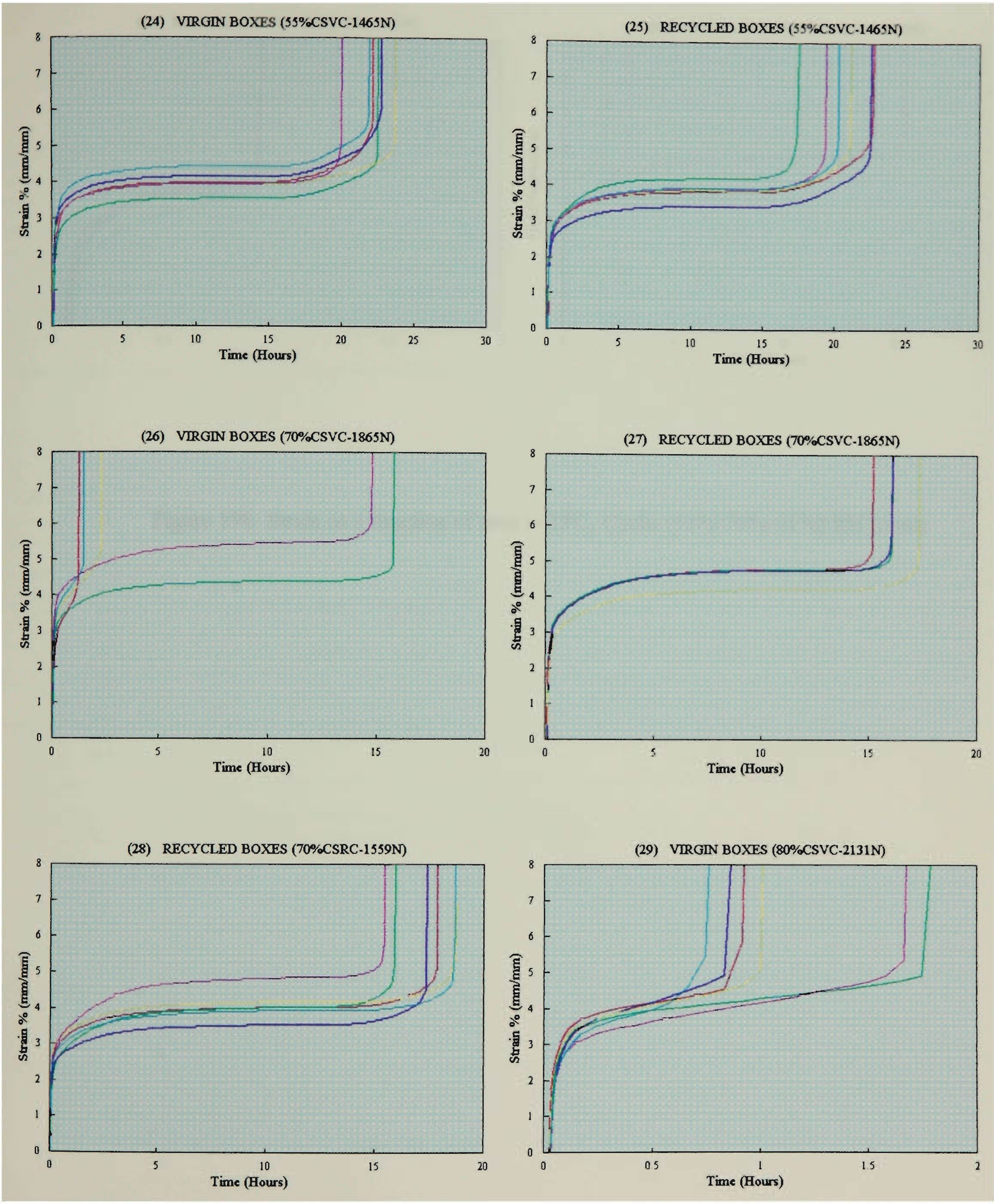


Figure 19b. Strain as a function of time -- 23°C, Cyclic (91%-70%-91%) RH (cont)

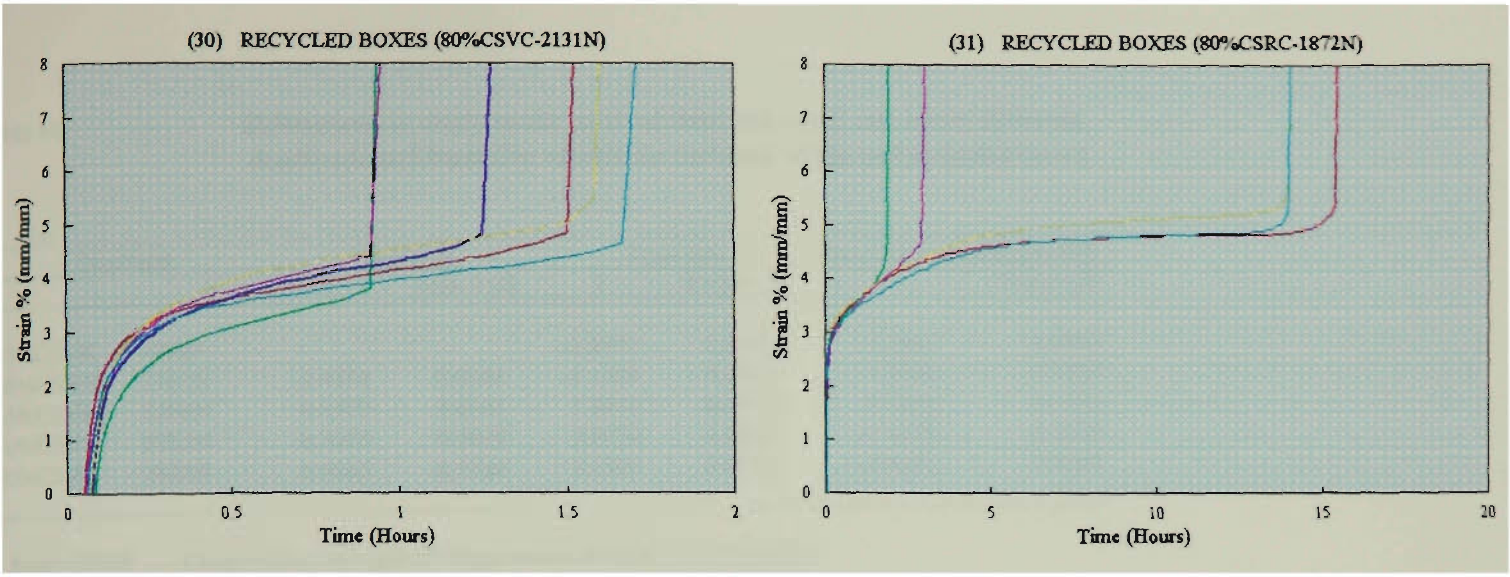


Figure 19b. Strain as a function of time -- 23°C, Cyclic (91%-70%-91%) RH (cont)

Table 14 Differences in creep strain survival time and creep rate under different deadloads and humidity conditions between virgin and recycled boxes

(a)

Deadload		Strain %		Time (hr)		Creep Rate (mm/mm/hr10⁶)	
		T	Prob > |T|	T	Prob > |T|	T	Prob > |T|
33%CSVH	958N			-2.8997	0.0199	7.3862	0.0005
40%CSVH	1161N	-3.4354	0.0044	-1.1519	0.2767	1.2532	0.2322
55%CSVH	1596N	0.4599	0.6554	1.8442	0.0949	0.5870	0.5773
70%CSVH	2032N	-0.3045	0.7670	2.6070	0.0262	-1.4189	0.2029
80%CSVH	2322N	0.6265	0.5520	2.1302	0.0590	-3.4396	0.0063

Note: CSVH ---- Compression Strength of Virgin boxes at High (91%) humidity

(b)

Deadload			Strain %		Time (hr)		Creep Rate (mm/mm/hr10⁶)	
			T	Prob > |T|	T	Prob > |T|	T	Prob > |T|
VB	33% CSVH	958N			-2.5326	0.0342	4.6199	0.0010
RB	33% CSREH	890N						
VB	40%CS VH	1161N	-0.1972	0.8473	0.5704	0.6032	0.2227	0.8278
RB	40% CSREH	1079N						
VB	55% CSVH	1596N	1.5081	0.1624	3.8647	0.0031	-1.5002	0.1645
RB	55% CSREH	1483N						
VB	70% CSVH	2032N	-0.8502	0.4151	4.9728	0.0006	-2.1980	0.0761
RB	70% CSREH	1888N						
VB	80% CSVH	2322N	0.3283	0.7494	4.7999	0.0026	-6.4134	0.0001
RB	80% CSREH	2158N						

Note: CSVH ---- Compression Strength of Virgin boxes at High (91%) humidity
CSREH ---- Compression Strength of Recycled boxes at High (91%) humidity
VB ---- Virgin Boxes
RB ---- Recycled boxes

Table 14 Differences in creep strain survival time and creep rate under different deadloads and humidity conditions between virgin and recycled boxes (cont)

(c)

Deadload		Strain %		Time (hr)		Creep Rate (mm/mm/hr10^6)	
		T	Prob > |T|	T	Prob > |T|	T	Prob > |T|
33% CSVH	958N			-2.2825	0.0456	2.8537	0.0175
55% CSVC	1465N	-0.9573	0.3610	-1.7294	0.1144	1.7626	0.1243
70% CSVC	1865N	-0.2336	0.8231	1.9403	0.1460	-1.6726	0.1930
80% CSVC	2131N	-1.3495	0.2069	0.7163	0.4902	-0.1305	0.8988

Note: CSVH — Compression Strength of Virgin boxes at High (91%) humidity
CSVC —Compression Strength of Virgin boxes at Cyclic (91%-70%-91%) humidity

(d)

Deadload			Strain %		Time (hr)		Creep Rate (mm/mm/hr10^6)	
			T	Prob > |T|	T	Prob > |T|	T	Prob > |T|
VB	33% CSVC	879N			-1.2726	0.2218	1.7013	0.1250
RB	33% CSRC	735N						
VB	70% CSVC	1685N	-1.8193	0.1604	2.2031	0.1122	-1.6675	0.1940
RB	70% CSRC	1559N						
VB	80% CSVC	2131N						
RB	80% CSRC	1872N	-0.3945	0.7024	2.8277	0.0471	-5.7814	0.0003

Note: CSVC — Compression strength of virgin boxes at Cyclic (91%-70%-91%) humidity
CSRC — Compression Strength of Recycled boxes at Cyclic (91%-70%-91%) humidity
VB — Virgin Boxes
RB — Recycled boxes

6.3.2.2 Relation of Load to Survival Time

The relationship between the load and survival time may be seen by the test results shown in Table 15.

One of the most widely used methods of demonstrating the survival time and determining the survival time is by measuring the deflection or strain as a function of time, which were shown in Figures 19a and 19b. From Figure 20 we can see that in the regimes above and below the survival time there is a linear variation in strain with survival time, but in the vicinity of the survival time there is a change in slope of the curve which occurs over several hours. The survival time is taken as the point at which extrapolations of the two lines meet.

For boxes in cyclic humidity however, the survival time was taken as the cross point of the tangent line of the last peak and the line above survival time. Figure 21 shows the example.

Under 33%CSVH load at 91% RH, all recycled boxes failed within 30 hours, but most of the virgin boxes had not showed any signs of failure in 120 hours except two of them that failed within 68.2 hours. Under 33%CSVC&CSRC, both types of boxes did not fail inside 288 hours, except for one of the recycled boxes failed.

In order to distinguish the survival time between virgin and recycled boxes, we applied the predicted points as follows: In 91% RH, because the strain was not significantly different between Instron and creep testing for virgin boxes, a predicted point was obtained by calculating the intersection point between average strain (Instron, which was 0.049 mm/mm) and the line in the secondary region (strain versus time curve). Figure 22 is an example.

In cyclic RH, because the strain was significantly different between Instron and the creep test, the average strain of boxes which had failed[2] in creep testing were used for predicting survival time (0.0499 mm/mm for virgin boxes and 0.0542 mm/mm for recycled boxes respectively). Box survival time, after high and cyclic RH exposures, was compared between two box types using a t-test analysis (Appendix L). The results from the analysis are show in Table 14. The comparison and analysis are as follows:

---

[2] Boxed which had failed means those boxes which had been forced to fail gradually under 33%CSVH at cyclic RH after 200 hours.

Table 15 **The relationship of load and survival time**

23°C, 91% RH

Type of box	Actual deadload On box (N)	Ratio of deadload to static compression strength (%)	Survival time (hr) Median	Avg	Stds
VB	958±5	33%CSVH	*129.2	*223.0	*177.1
	1161±5	40%CSVH	19.5	21.4	15.1
	1596+5	55%CSVH	3.0	3.1	0.5
	2032±5	70%CSVH	1.3	1.3	0.2
	2322+5	80%CSVH	0.5	0.6	0.1
RB	890+5	33%CSREH	44.8	48.4	20.2
	958+5	33%CSVH	19.8	20.3	5.7
	1079+5	40%CSREH	15.5	22.4	17.4
	1161+5	40%CSVH	14.3	14.0	2.2
	1483±5	55%CSREH	4.2	4.3	0.6
	1596+5	55%CSVH	3.4	3.5	0.3
	1888±5	70%CSREH	1.9	1.9	0.3
	2032±5	70%CSVH	1.6	1.6	0.3
	2158+5	80%CSREH	1.2	1.2	0.3
	2322+5	80%CSVH	0.8	0.8	0.2

Note: VB ---- Virgin box
RB ---- Recycled box
CSVH ---- Compression Strength of Virgin boxes at High (91%) humidity
CSREH ---- Compression Strength of Recycled boxes at High (91%) humidity
* ---- Predicted value

23°C, Cyclic RH

Type of box	Actual Deadload On box (N)	Ratio of deadload to static compression strength (%)	survival Time (hr) Median	Avg	Stds
VB	958±5	33%CSVH	*294.3	*320.5	*138.4
	879±5	33%CSVC	*515.6	*457.9	*207.1
	1465±5	55%CSVC	22.3	22.1	1.3
	1865±5	70%CSVC	2.4	7.1	7.5
	2131±5	80%CSVC	0.9	1.1	0.5
RB	958±5	33%CSVH	*196.9	*183.0	*51.0
	735±5	33%CSRC	*218.6	*323.0	*241.5
	1465±5	55%CSVC	20.7	20.5	1.9
	1559±5	70%CSRC	17.5	17.2	1.3
	1865±5	70%CSVC	16.1	16.2	0.8
	1782+5	80%CSRC	14.0	9.6	6.7
	2131±5	80%CSVC	1.4	1.3	0.3

Note: VB ---- Virgin box
RB ---- Recycled box
CSVC ---- Compression Strength of Virgin boxes at Cyclic (91%-70%-91%) humidity
CSRC ---- Compression Strength of Recycled boxes at Cyclic (91%-70%-91%) humidity
* ---- Predicted value

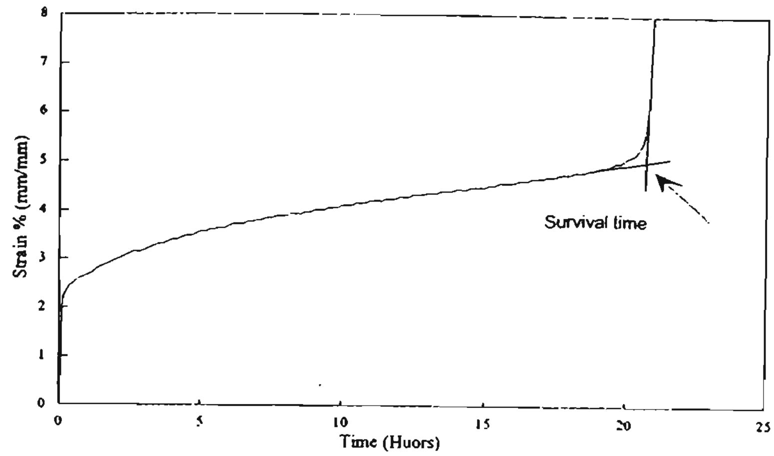


Figure 20. Survival time of boxes at constant RH

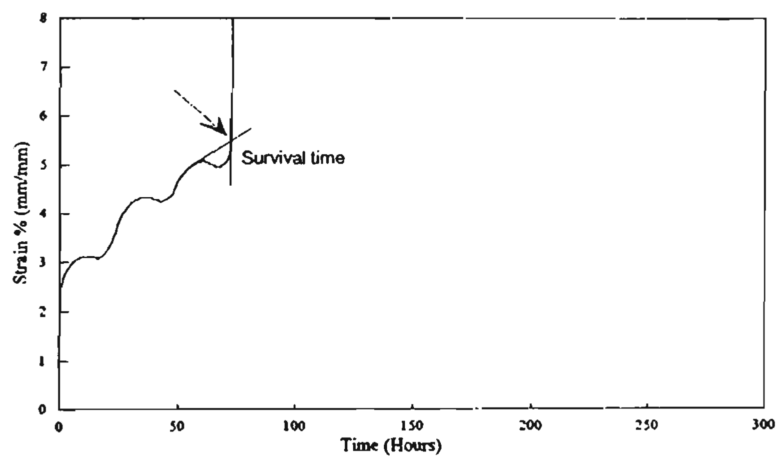


Figure 21. Survival time of boxes at cyclic RH

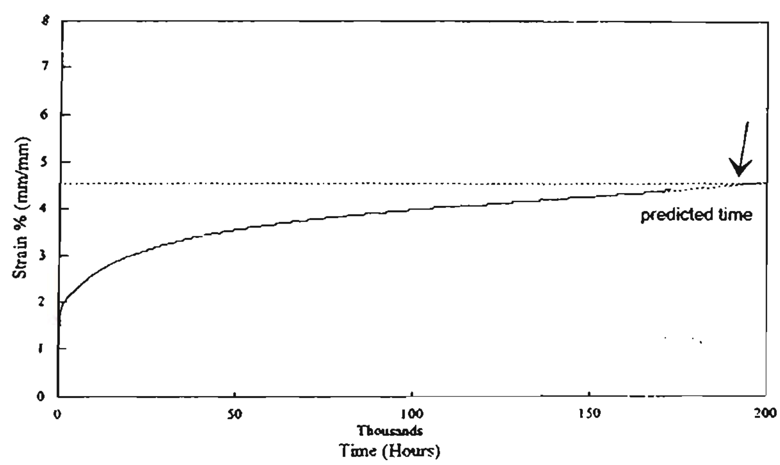


Figure 22. Predicted point of survival time of boxes

Boxes under the same load levels

- At the 95% confidence level, significant differences of survival time were found (under the same load levels of 33%, 70%, and 80%CSVH at 91% RH) between two box types.

- At the 95% confidence level, a significant difference of survival time was found (under the same load level of 33%CSVH) at cyclic RH between the two box types.

These test results show that at 91% RH, virgin and recycled boxes performed differently under deadloads of 70%, 80% and 33%CSVH.

For higher loads (70% and 80%CSVH), all boxes failed within 2 hours. Recycled boxes lasted longer than virgin boxes. This is because recycled boxes started with higher compression strength. In other words, the average compression strength of a recycled box was 300 N higher than a virgin box at 23°C, 50% RH. Due to the fact that all boxes were transferred from ISO condition (50% RH) to high humidity (91% RH) condition right away, the moisture contents did not reach the equilibrium.

The presence of a high moisture absorption rate also promoted the virgin boxes to fail soon within short time. The performance of corrugated fibreboard boxes are significantly affected by the moisture content. Recycled materials pick up moisture at a lower rate (Figure 18) than virgin materials because drying on the paper machine causes irreversible humification of the fibre surface reducing bond sites available when reslushed compared to never dried pulp. This is a significant aspect in favour of recycled boxes when exposed to high humidity environments in a short time. Further investigation needs to be carried out to explore these behaviors further.

For lower load (33%CSVH), virgin boxes survived longer than recycled boxes. This is because after moisture contents reached equilibrium, the effect of moisture content on recycled boxes would be greater than on virgin boxes. Once again, this was dependent on the composition of recycled board. The fibre in the paper used to manufacture the recycled boxes had experienced at least two pulpings, their fibres were made shorter and the strength properties paper made from this fibre will reduced. To compensate for this a quantity of starch is added to paper to strengthen the fibre to fibre bonding, improving their strength. This starch, at the same time, will react with moisture and this may contribute to low compression strength and shorter survival time of boxes when humidity was high.

In cyclic RH, the differences of survival time were not significant under 70% and 80% CSVC between two box types, it was only significant under 33% CSVH. The reason for this is that the high deadloads were taken from the compression strength of virgin boxes at cyclic RH which were lower than 70% and 80% CSVH. Hence, boxes lasted relatively longer in cyclic RH. This also allowed moisture a longer time to act on the boxes resulting in lower compression strength for both box types so that survival time of virgin and recycled boxes were not significantly different under 70% and 80% CSVC.

For lower load (33%CSVH), virgin boxes survived longer than recycled boxes. This is because after moisture contents reached equilibrium, the effect of moisture content on recycled boxes would be greater than on virgin boxes. Once again, this was dependent on the composition of recycled board. Those recycled boxes had experienced at least two pulpings, their fibres were made shorter, and ECT value and box compression strength were therefore decreased. There were large quantities of starch in recycled boxes to strengthen the fibre to fibre bonding, improving their strength. This starch, at the same time, was soluble in moisture which resulted in low compression strength and shorter survival time of boxes when humidity was high.

In cyclic RH, the differences of survival time were not significant under 70% and 80% CSVC between two box types, it was only significant under 33% CSVH. The reason for this is that the high deadloads were taken from the compression strength of virgin boxes at cyclic RH which were lower than 70% and 80% CSVH. Hence, boxes lasted relatively longer in cyclic RH. This also allowed moisture a longer time to act on the boxes resulting in lower compression strength for both types so that survival time of virgin and recycled boxes were not significantly different under 70% and 80% CSVC.

<u>Boxes under the proportional load levels</u>

- At the 95% confidence level, the significant differences of survival time were found (under all deadloads except 40% CSVH&CSREH in 91% RH) between two box types.

- At the 95% confidence level, a significant difference of survival time was found (under 80% CSVC&CSRC in cyclic RH) between the two box types.

Since the compression strength of virgin boxes was significantly different from recycled boxes at cyclic RH, creep tests for boxes under the proportional load levels were completed to find out if they would perform in a like manner. The proportional load is a deadload calculated as a percentage of the compression strength. For example, 40%CSVH&CSREH means that the deadload for virgin boxes was 40%CSVH and for recycled boxes was 40%CSREH.

These results show that virgin and recycled boxes performed differently under proportional load levels, except 40%CSVH&CSREH at 91% RH. At cyclic RH, the performance was not significantly different, except 80%CSVC&CSRC.

From both the same and proportional load tests, it is concluded that whether under the same load levels or the proportional load levels, virgin and recycled boxes performed differently at 91% RH. For cyclic RH, they performed differently under the same low load level (33%CSVH), but it was not significantly different under the low proportional load level (33%CSVC&CSRC).

6.3.2.3 Predicting survival time with constant load

If we plot the results (without predicted points) obtained at 91% RH (Table 15) as constant load vs. $Log_{10}t$ (base 10 logarithm of time, t, in hours) and fit two regression lines with using least squares, we get Figure 23a.

The equations of these lines are as follows:

$$t = 10^{\frac{[2061-L]}{716}} \quad \text{(VB)} \qquad R^2=0.94 \qquad (12)$$
$$t = 10^{\frac{[2116-L]}{807}} \quad \text{(RB)} \qquad R^2=0.93 \qquad (13)$$

From the figure, we can see that there is not much difference between virgin and recycled boxes. However, if we inspect Figure 23b which includes the predicted points, a significant difference appears.

In Figure 23b, it is apparent that simply fitting a regression line is not the best way. Using two linear-log regression lines, high load (≥55%CSVH) and low load (≤55%CSVH), a more reasonable fit is obtained. It also follows Caulfield's theory (1985) and Kellicutt and Landt's (1951) work.

In order to make use of testing data obtained from both pre-testing and testing, 8 extra points (4 points for each type of box) were also included in the graphs. The deadloads used were 25% and 30%CSVH&CSREH. During testing three recycled boxes failed and for the remaining boxes, survival times were predicted.

The equations of these lines are as follows:
High load region:

$$t = 10^{\frac{[2089-L]}{963}} \quad \text{(VB)} \qquad R^2=0.95 \qquad (14)$$
$$t = 10^{\frac{[2182-L]}{968}} \quad \text{(RB)} \qquad R^2=0.87 \qquad (15)$$

Low load region:

$$t = 10^{\frac{[1624-L]}{308}} \quad \text{(VB)} \qquad R^2=0.83 \qquad (16)$$
$$t = 10^{\frac{[1827-L]}{586}} \quad \text{(RB)} \qquad R^2=0.84 \qquad (17)$$

Figures 24a and 24b show the data obtained for cyclic RH (Table 15) plotted in the form load (N) versus the logarithm of time (hrs). The equations of the four regression lines, obtained by least squares, are as follows:

(23°C, cyclic RH):

$$t = 10^{\frac{[2086-L]}{406}} \qquad \text{(VB)} \qquad R^2=0.80 \qquad (18)$$

$$t = 10^{\frac{[2153-L]}{416}} \qquad \text{(RB)} \qquad R^2=0.70 \qquad (19)$$

Including predictions (23°C, cyclic RH):

$$t = 10^{\frac{[2102-L]}{458}} \qquad \text{(VB)} \qquad R^2=0.78 \qquad (20)$$

$$t = 10^{\frac{[2264-L]}{583}} \qquad \text{(RB)} \qquad R^2=0.69 \qquad (21)$$

The cyclic RH data are very scattered This is because some of the boxes failed around the peak of first cycle, while the others failed around the peak of subsequent cycles.

Kellicutt and Landt (1951) found a relationship between maximum stacking load, mean box compression strength, and survival time that could be described by:

$$L_{max} / W_{st} = m \operatorname{Log}_{10} t/t_0 + b \qquad (22)$$

Where: L_{max} = maximum stacking load (N)

W_{st} = mean box compression strength (N)

t = survival time (days)

t_0 = constant arbitrarily chosen as 1 (day)

This relationship has been proved valid by Stott (1959), and Moody & Skidmore (1966). Table 16 shows the results of this and previous studies.

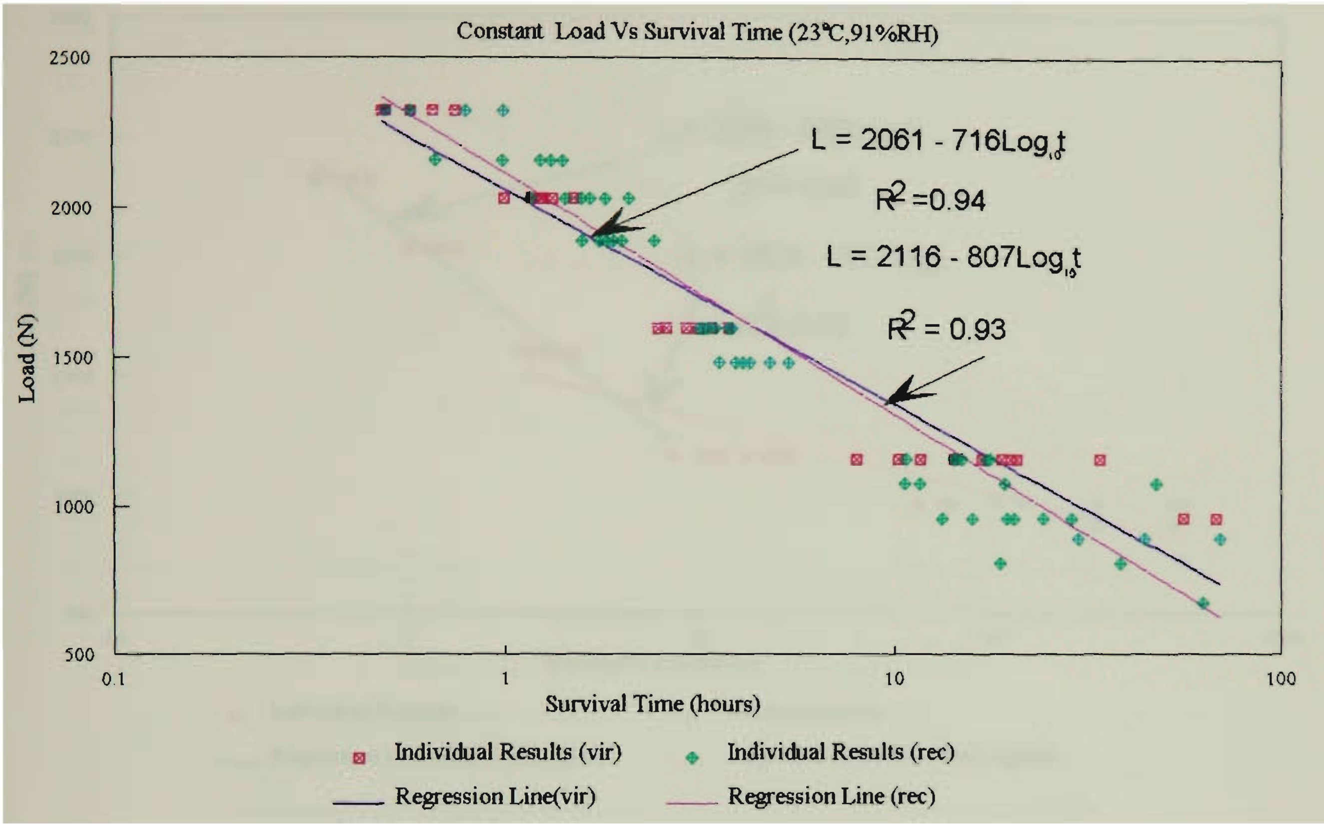
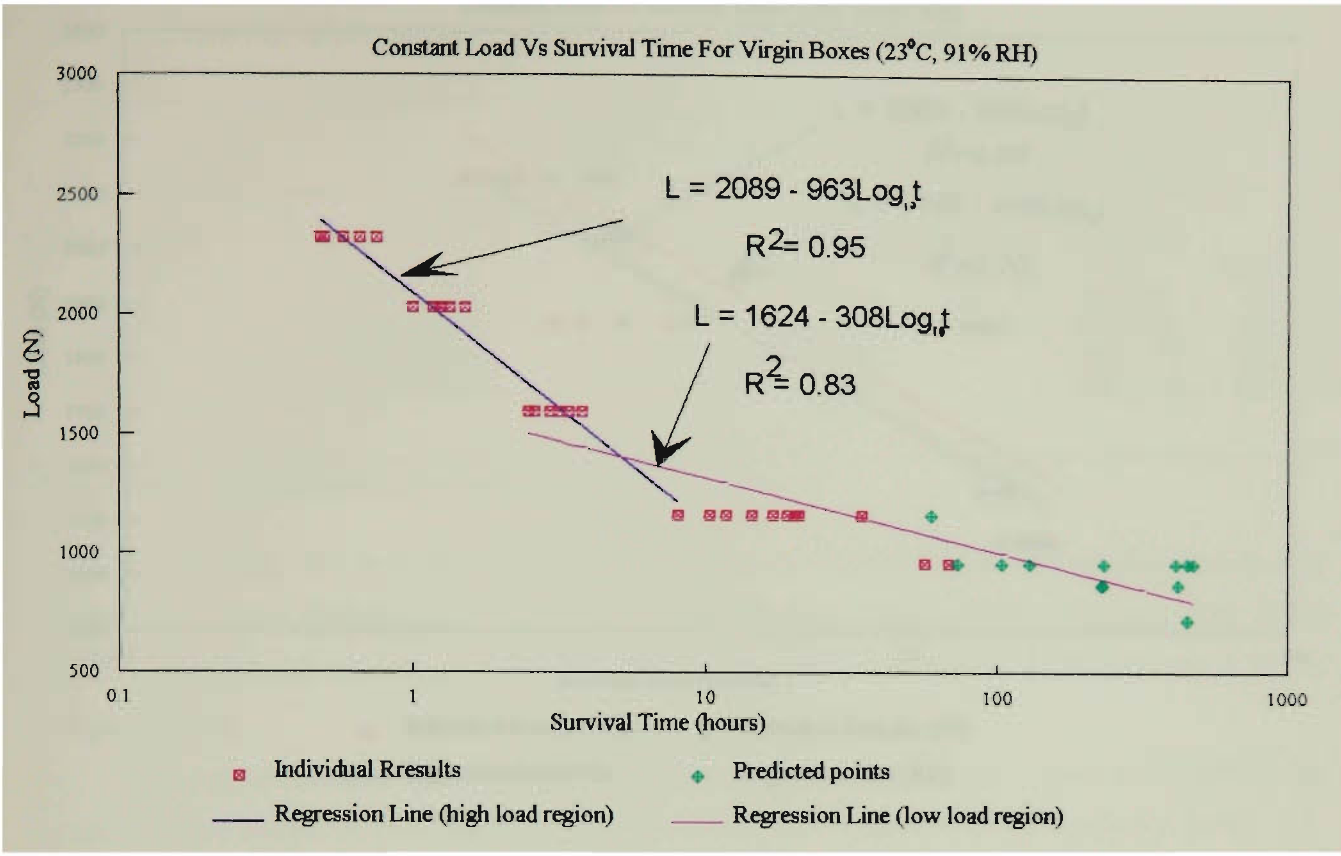


Figure 23a. Constant load vs. survival time (23°C, 91% RH)



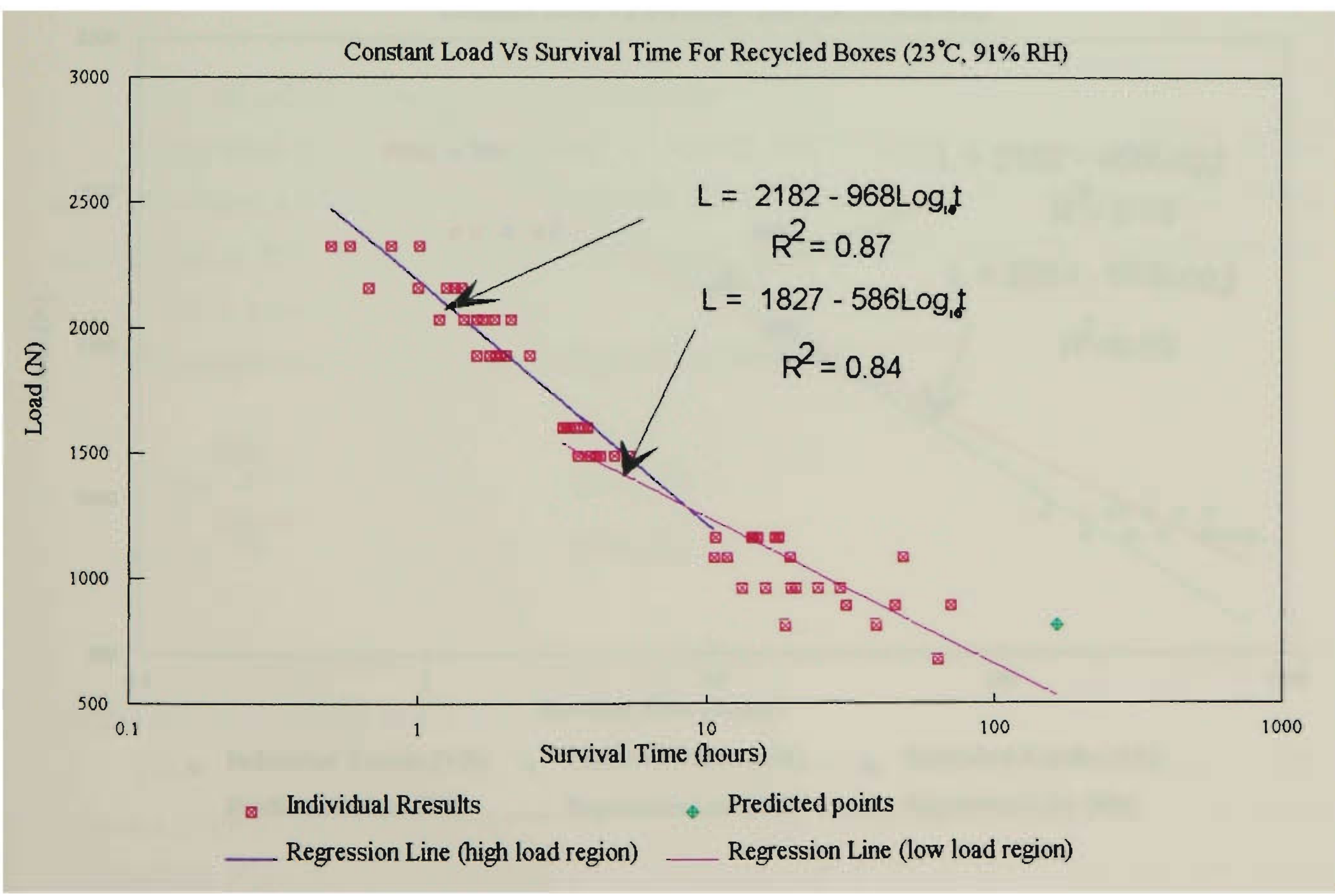


Figure 23b. Constant load vs. survival time (23°C, 91% RH)

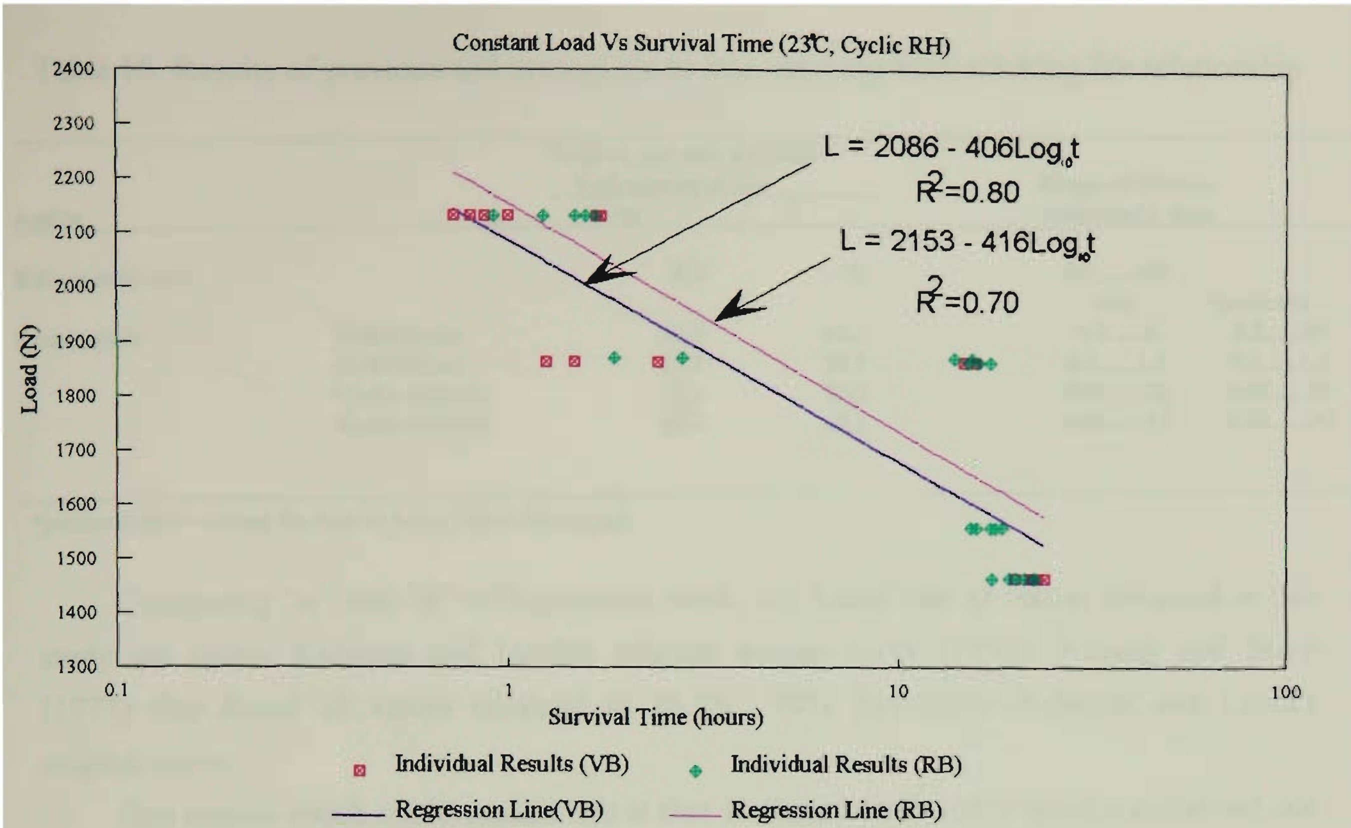


Figure 24a. Constant load vs. survival time (23°C, Cyclic RH)

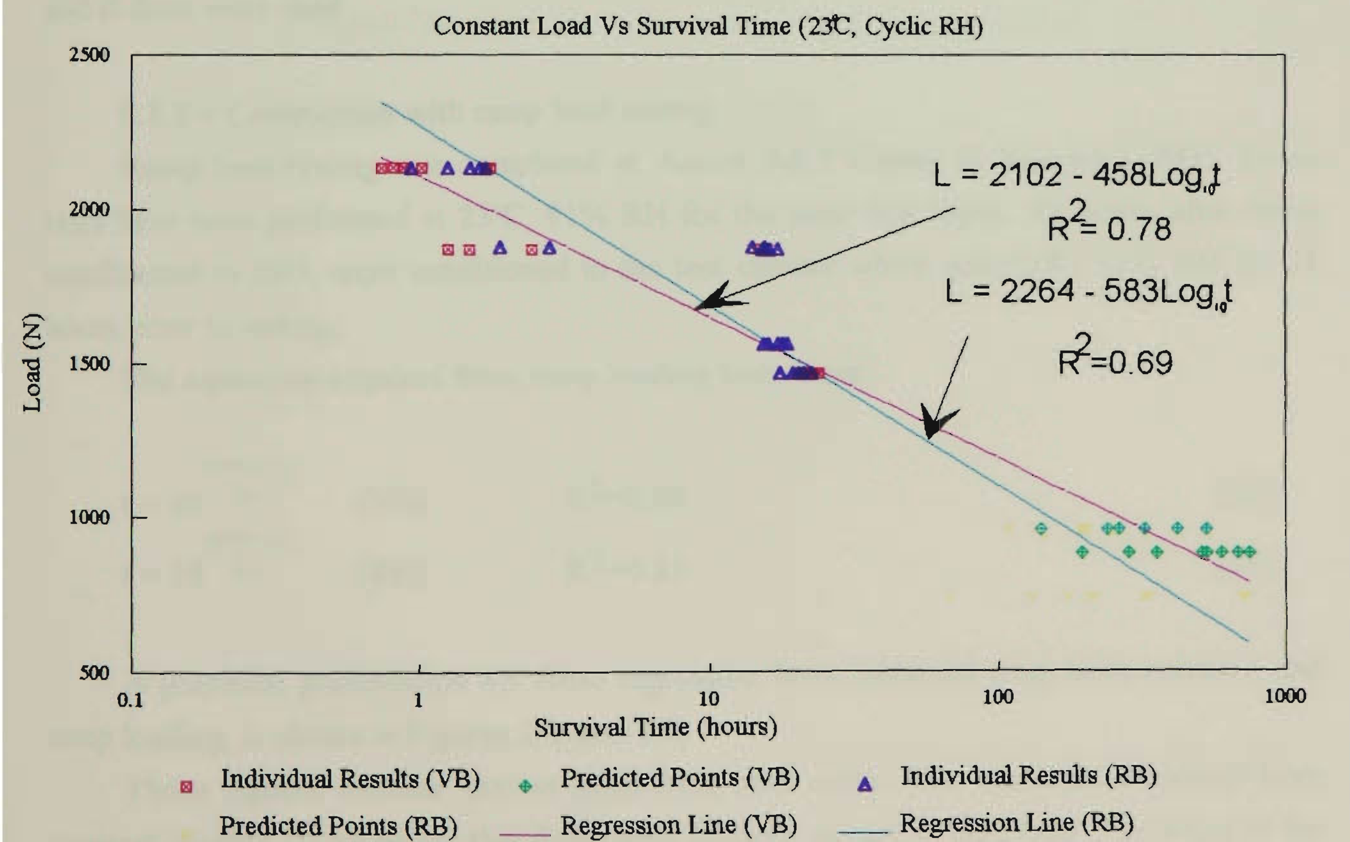


Figure 24b. Constant load vs. survival time (23°C, Cyclic RH)

Table 16. Results of previous and present study into stacking load-stacking life relationship

Author		Slope m and axis intercept b of regression line -m	b	Range of lifetime measured t_L days real	*predicted
Killcutt and Landt		8.8	72	0.2......100	
Present study	91%RH(vir)	10.6	41.2	0.2......8	0.2......20
	91%RH(rec)	21.7	37.7	0.2......1.5	0.2......1.5
	Cyclic RH(vir)	17.1	55.2	0.02......12	0.02......30
	Cyclic RH(rec)	26.3	65.1	0.02......12	0.02......30

*predicted time—using the data of boxes which did not fail

Comparing "m" and "b" with previous work, we found that all values obtained in this study are below Kellicutt and Landt's original design curve (1951). Koning and Stern (1977) also found all values obtained at 26.7°C, 90% RH below Kellicutt and Landt's original curve.

One reason which could explain this is that Kellicutt and Landt's word was carried out over a wider range of five levels of temperatures and seven levels of humidity (-6.6, 0.5, 22.7, 23.8, and 26.6°C and 30%, 50% 64%, 65%, 80%, 90%, and 96% RH) where both A and B flute were used.

6.3.2.4 Comparison with ramp load testing

Ramp load testing was completed at Amcor R&T Center by Seevers (1993). These tests have been performed at 23°C, 91% RH for the same box types. All boxes after being conditioned in ISO, were conditioned in the test climate which was 23°C, 91% RH for 24 hours prior to testing.

The equations acquired from ramp loading tests were:

$$t = 10^{\frac{[2042-L]}{264}} \quad \text{(VB)} \qquad R^2=0.89 \qquad (23)$$

$$t = 10^{\frac{[1761-L]}{242}} \quad \text{(RB)} \qquad R^2=0.83 \qquad (24)$$

A graphical presentation for these regression lines, obtained from both constant and ramp loading, is shown in Figures 25a and 25b.

Those figures indicate that at both 91% and cyclic RH, the lines obtained from constant loading are all below that from ramp loading, except at high load. The slope of the line derived from the low load region was quite similar to the slope of the line from ramp loading for virgin boxes.

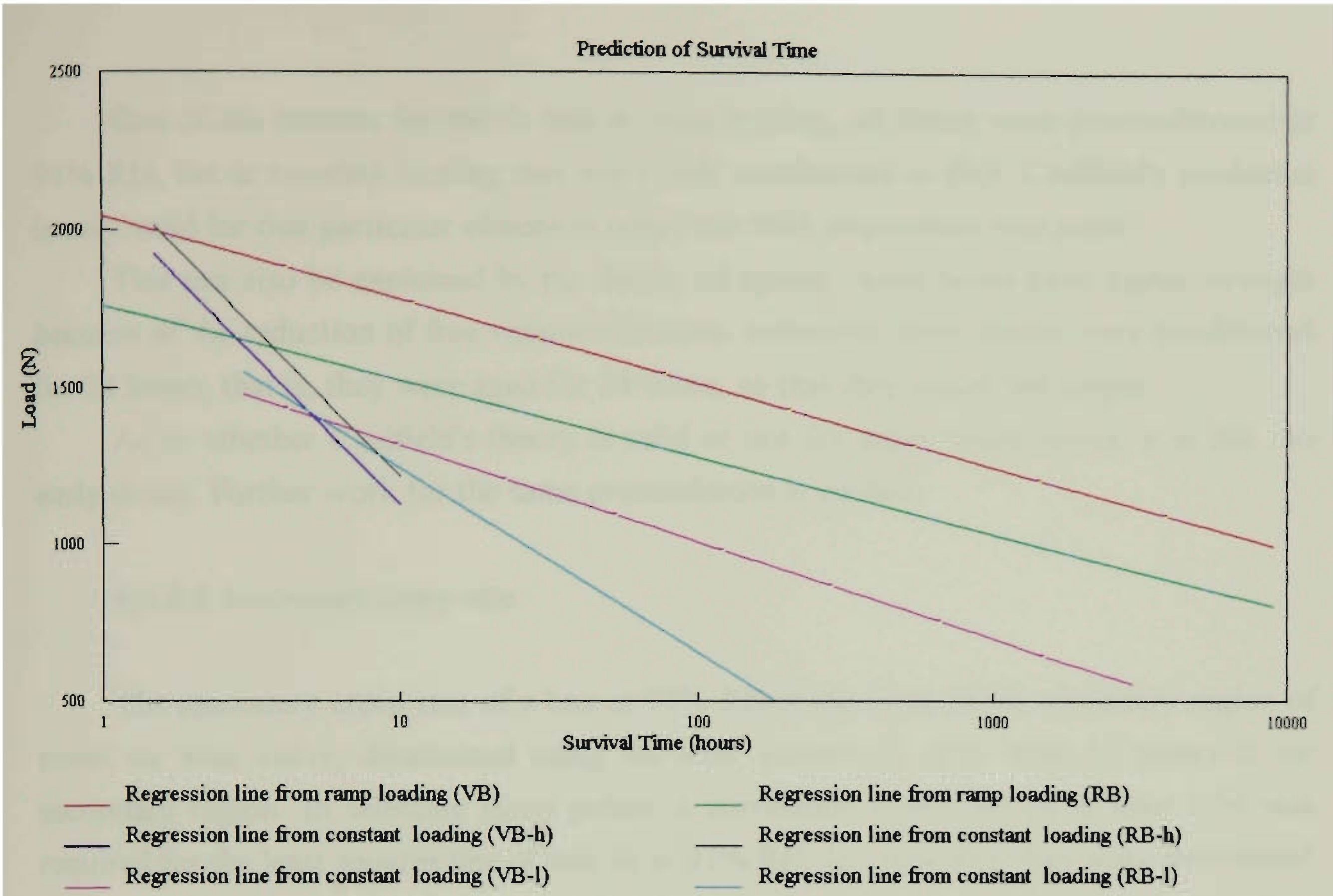


Figure 25a. Prediction of survival time (23°C, Cylic RH)

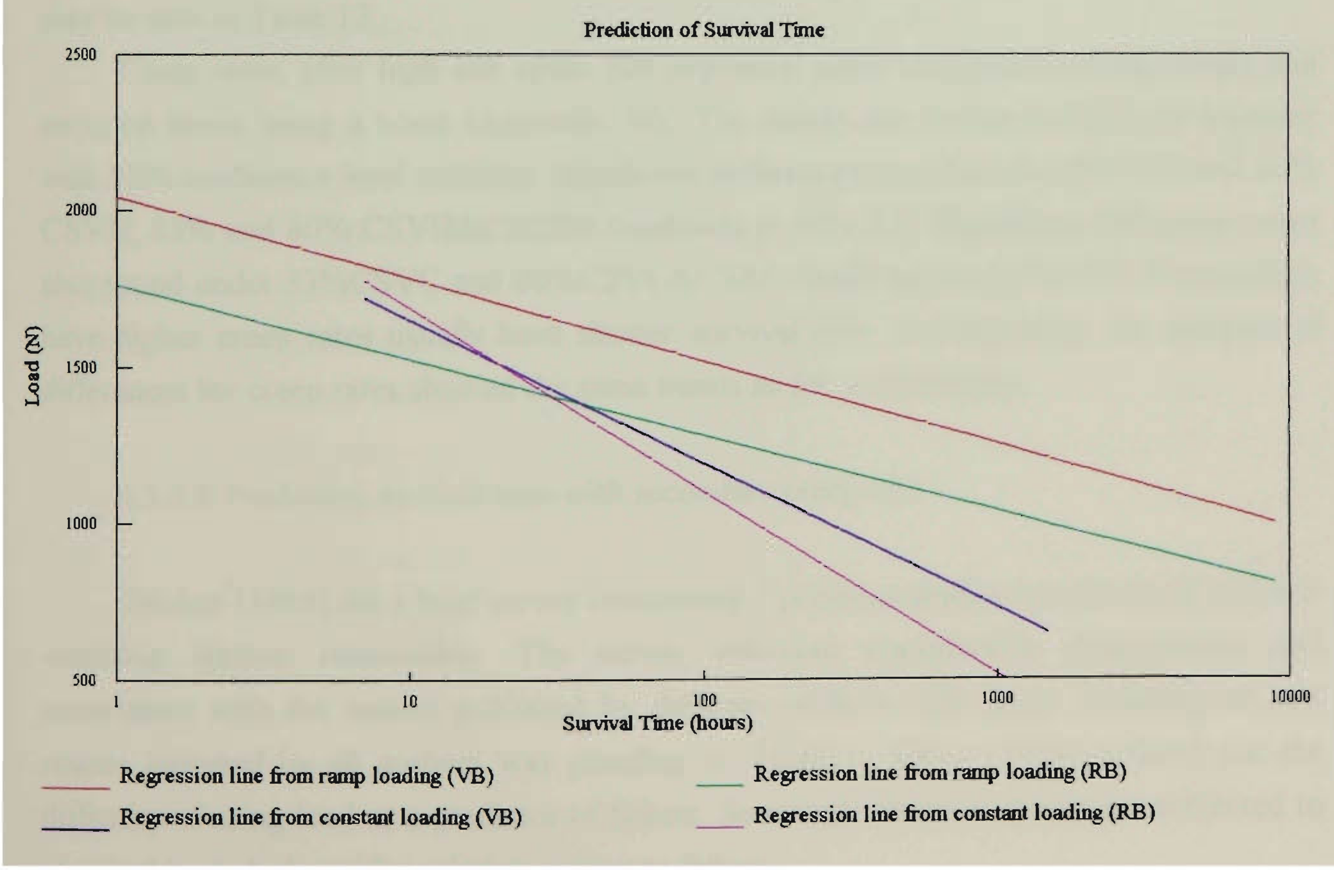


Figure 25b. Prediction of survival time (23°C, Cylic RH)

One of the reasons for this is that in ramp loading, all boxes were preconditioned at 91% RH, but in constant loading they were only conditioned at ISO. Caulfield's prediction is only valid for that particular climate in which the ROL experiment was made.

This can also be explained by the theory of ageing. Aged boxes have higher strength because of the reduction of free volumes between molecules. Here, boxes were conditioned for 24 hours, that is, they were aged for 24 hours, so that they would last longer.

As to whether Caulfield's theory is valid or not for paper board boxes, it is still too early to say. Further work for the same preconditions is needed.

6.3.2.5 Secondary creep rate

The secondary creep rate of a box at 91% RH is the slope of the secondary region of strain vs. time curve, determined using the least squares fit of at least 10 points in the secondary region. In selecting those points, a correlation coefficient of at least 0.94 was required for the least squares line of best fit at 91% RH. In cyclic RH, they were determined using the least squares fit of more than 100 points among the last 3 peaks in the secondary region in the strain vs. time curves. The relationship between creep rate and survival time may be seen in Table 13.

Creep rates, after high and cyclic RH exposure, were compared between virgin and recycled boxes using a t-test (Appendix M). The results are shown in Table 14 together with 95% confidence level statistics. Significant differences were found under 33% and 80% CSVH, 33% and 80% CSVH&CSREH deadloads at 91% RH. Significant differences were also found under 33%CSVC and 80%CSVC&CSRC deadloads in cyclic RH. Boxes which have higher creep rates usually have shorter survival time. Consequently, the analyses of differences for creep rates showed the same trends as for survival time.

6.3.2.6 Predicting survival time with secondary creep rate

Thielert (1984) did a brief survey comprising 7 previous studies into the stacking load--stacking lifetime relationship. The survey indicated considerable disagreement and uncertainty with the results published by different authors. The great variability of test results reported by all authors was puzzling to Thielert. Alfrey (1948) pointed out the difficulty of using load as a predictor of failure. Seemingly identical specimens subjected to identical loads had a wide variation in time to failure.

Obviously, another method is desirable for prediction purposes.

Figures 26a and 26b shows that the secondary creep rate may be used as a predictor of survival time. A linear regression of those points gave the following results.

(23°C, 91% RH):

$$t = \frac{11614}{C_r^{0.95}} \qquad \text{(VB)} \qquad R^2=0.99 \tag{25}$$

$$t = \frac{34182}{C_r^{1.07}} \qquad \text{(RB)} \qquad R^2=0.99 \tag{26}$$

Including predictions (23°C, 91% RH):

$$t = \frac{7452}{C_r^{0.91}} \qquad \text{(VB)} \qquad R^2=0.98 \tag{27}$$

$$t = \frac{27818}{C_r^{1.05}} \qquad \text{(RB)} \qquad R^2=0.99 \tag{28}$$

Where: t = survival time (hours)

C_r= creep rate in secondary region (10^6 mm/mm/hr)

From Figures 26a and 26b, it is seen that the points are well aligned, even though the data was widely scattered when relating time to failure and load.

This relationship not only proved Koning and Stern's point (1977) connecting secondary creep rate and survival time, but also showed the validity of Alfrey's (1948) point using a property from the process (C_r) to predict failure.

Figure 26a shows that the two regression lines have a cross point. When values in the "x" axis are less than this point, especially when deadload is high, such as 80% CSVH, the creep rate of a virgin box will be higher than that of a recycled box, for the same failure time. On the contrary, in low load, such as 33%CSVH, for the same survival time, a recycled box will have a higher creep rate than a virgin box. For the same creep rate, virgin boxes will fail first, but their creep rates are never the same. The creep rates are not significantly different around the cross point between two box types, as the t-test showed that failure times and creep rates were not significantly different under 40%, 50%CSVH. The same applies for results shown in Figure 26b.

Figures 27a and 27b derived from Table 13, in cyclic RH, show lines that can be described by the equations:

(23°C, cyclic RH):

$$t = \frac{366}{C_r^{0.62}} \qquad \text{(VB)} \qquad R^2=0.98 \qquad (29)$$

$$t = \frac{341}{C_r^{0.58}} \qquad \text{(RB)} \qquad R^2=0.98 \qquad (30)$$

Including predictions (23°C, cyclic RH):

$$t = \frac{7600}{C_r^{0.99}} \qquad \text{(VB)} \qquad R^2=0.91 \qquad (31)$$

$$t = \frac{29308}{C_r^{1.13}} \qquad \text{(RB)} \qquad R^2=0.74 \qquad (32)$$

Figure 27b shows that the data was very scattered for cyclic RH. The boxes failed at significantly different times even though they were the same type of box having the same creep rate.

The group of data in the middle of the curve represents those boxes which were under a high load and failed in less than one cycle (24 hours), where the average moisture content in those boxes is thereby low. The group of data on the right hand side however, relates to boxes that had a low load and some of them did not fail in 11 cycles, where the average moisture content in these boxes was higher compared to boxes which had less than one cycle. Because the behavior of boxes depends on both moisture and deadload, This indicates that some of boxes had the same creep rate, but different survival times.

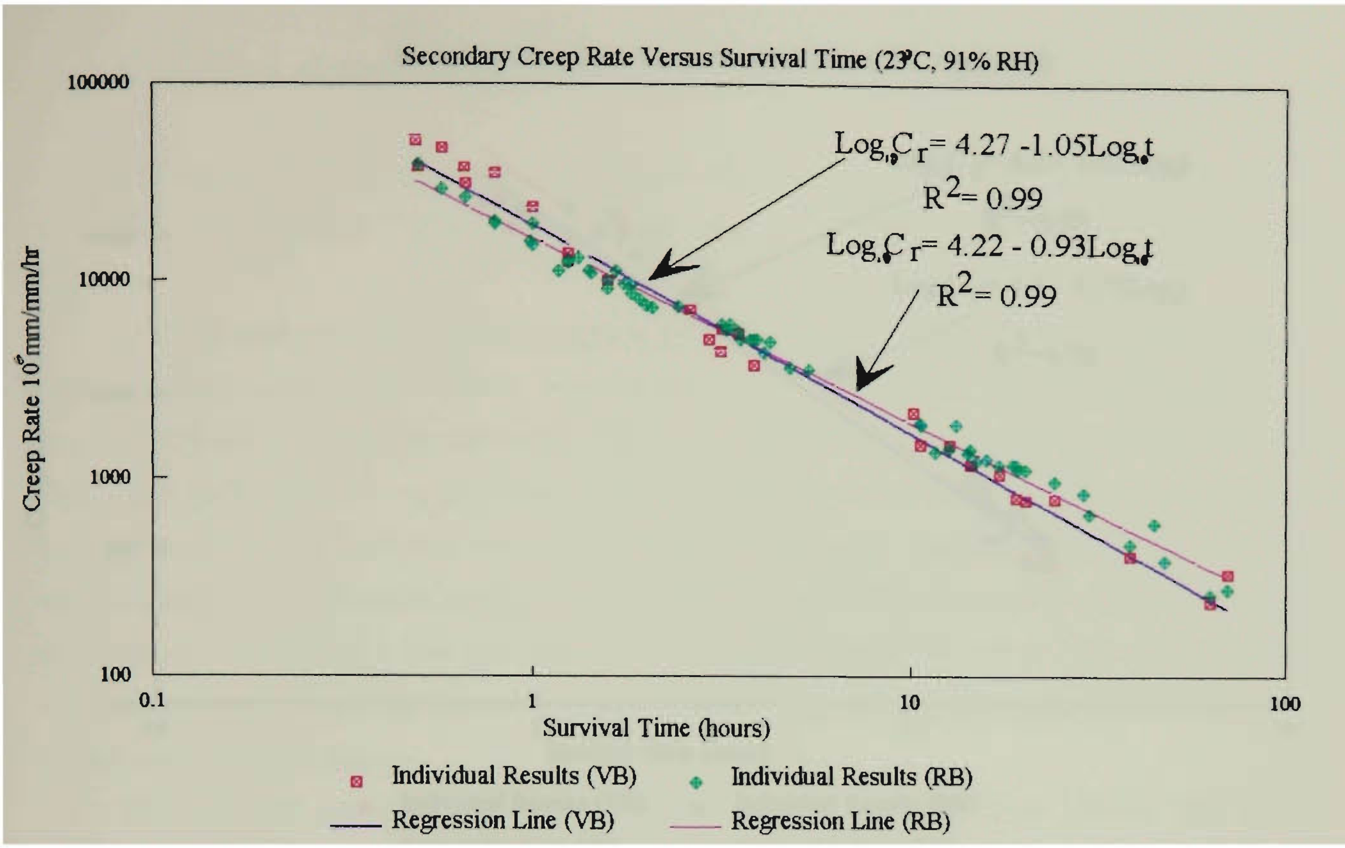


Figure 26a. Secondary creep rate vs. survival time (23°C, 91% RH)

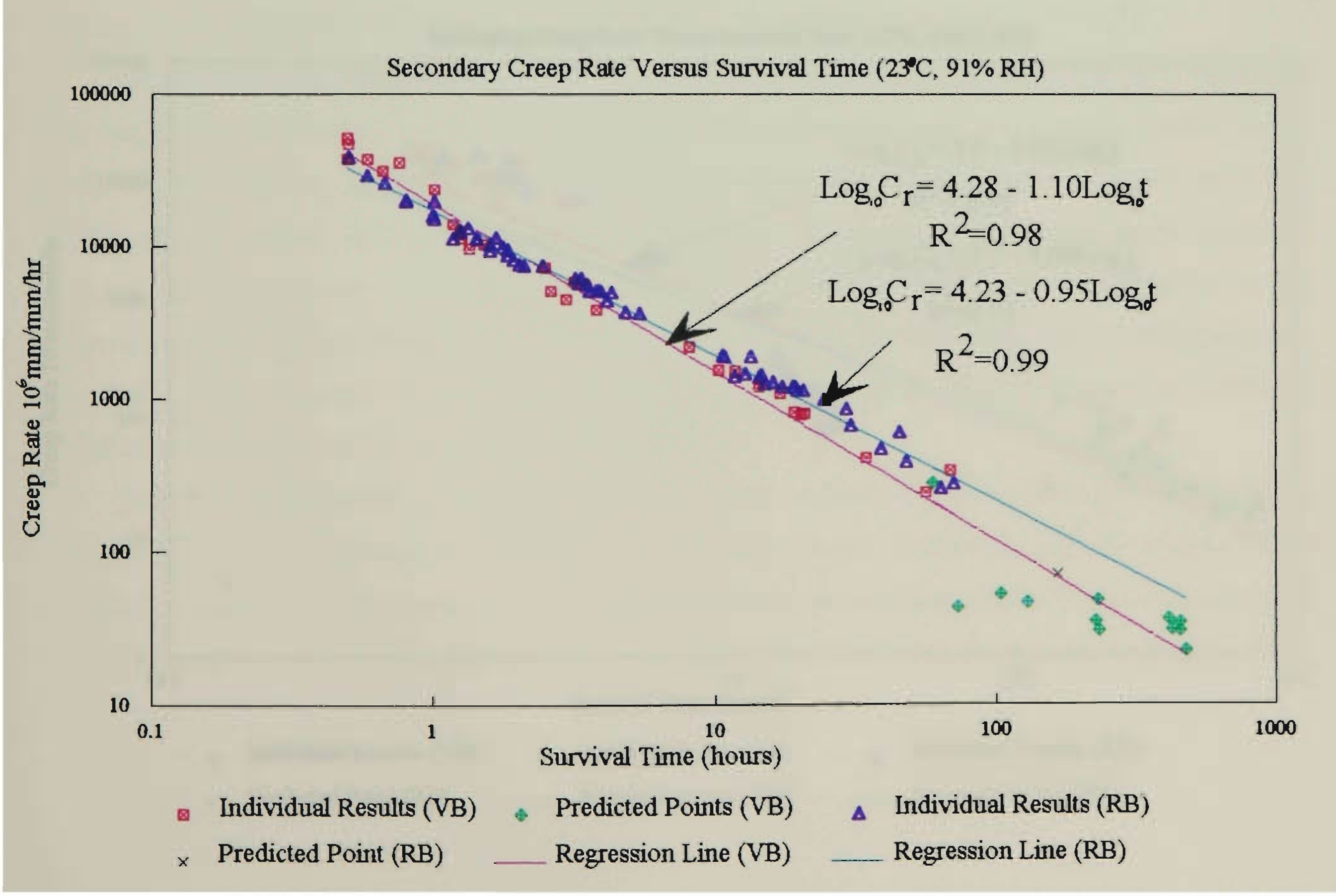


Figure 26b. Secondary creep rate vs. survival time (23°C, 91% RH)

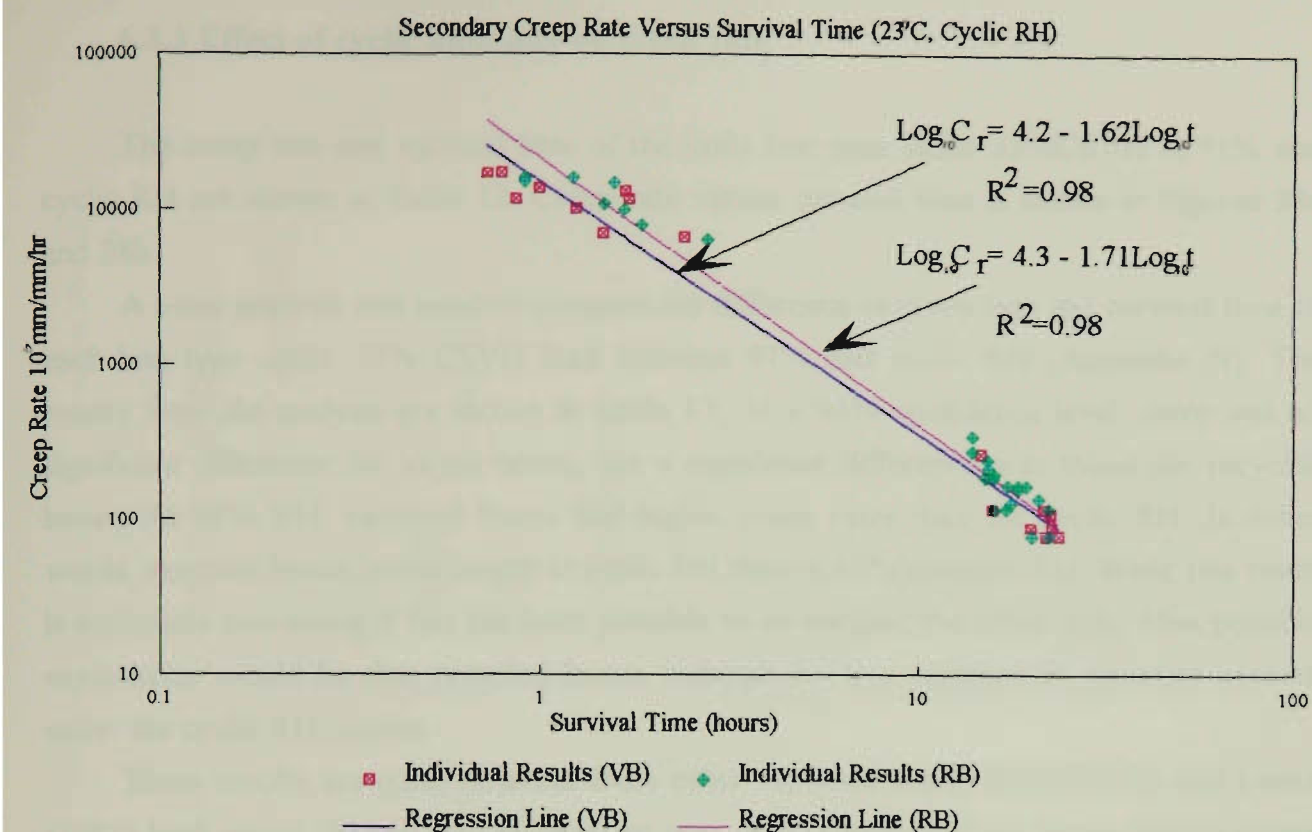


Figure 27a. Secondary creep rate vs. survival time (23°C, Cyclic RH)

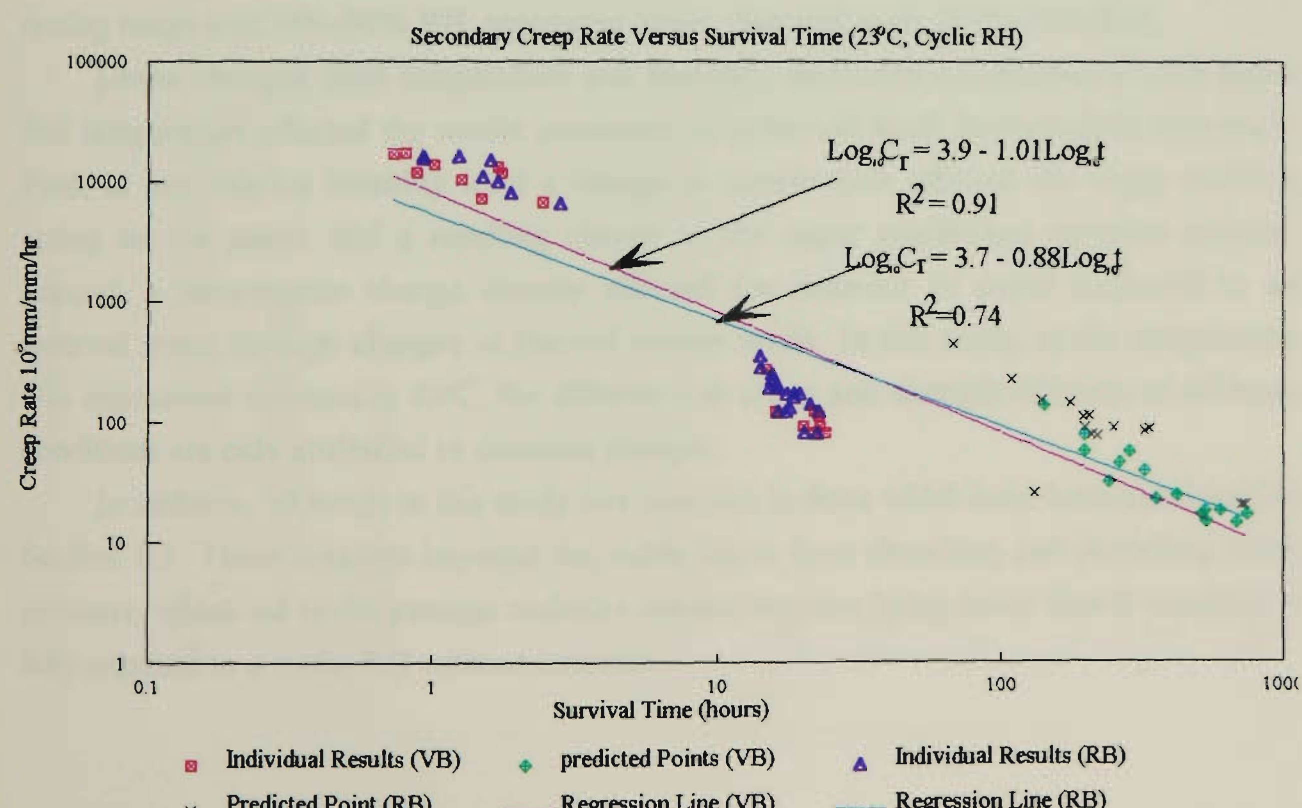


Figure 27b. Secondary creep rate vs. survival time (23°C, Cyclic RH)

6.3.3 Effect of cyclic humidity on creep rate

The creep rate and survival time of the same box type under 33%CSVH at 91% and cyclic RH are shown in Table 13. Creep rate versus survival time is shown in Figures 28a and 28b.

A t-test analysis was used to compare the difference of creep rate and survival time of each box type under 33% CSVH load between 91% and cyclic RH (Appendix N). The results from the analysis are shown in Table 17. At a 95% confidence level, there was no significant difference for virgin boxes, but a significant difference was found for recycled boxes. At 91% RH, recycled boxes had higher creep rates than for cyclic RH. In other words, recycled boxes lasted longer in cyclic RH than in 91% constant RH. While this result is extremely interesting it has not been possible to investigate the effect fully. One possible explanation would be that recycled boxes undergo far less variation in moisture content under the cyclic RH regime.

These results are quite different from other reported work. Byrd (1972) and Leake (1982) both stated that cyclic environment was more detrimental for boxes than constant RH, even though the average moisture content of a box was lower in cyclic condition.

However, Byrd tested for boards which were more sensitive to the moisture, and his testing range was 35%-90% RH, somewhat larger than this study (70%-91% RH).

Leake changed both temperature and humidity environments. Benson (1971) found that temperature affected the tensile properties of softwood Kraft linerboards in two ways: First, at any relative humidity level a change in temperature affected the vapor pressure acting on the paper, and a resulting change in the paper equilibrium moisture content. Second, a temperature change directly affected the behavior of paper subjected to an external stress through changes in thermal energy levels. In this study, as the temperature was maintained constant at 23°C, the difference in creep and strength of boxes at different conditions are only attributed to moisture changes.

In addition, all boxes in this study had contents in them which have been mentioned in Section 5.5. These contents impeded the inside liners from absorbing and desorbing much moisture, which led to the average moisture content in a box being lower than it would be if fully exposed to a cyclic RH without contents.

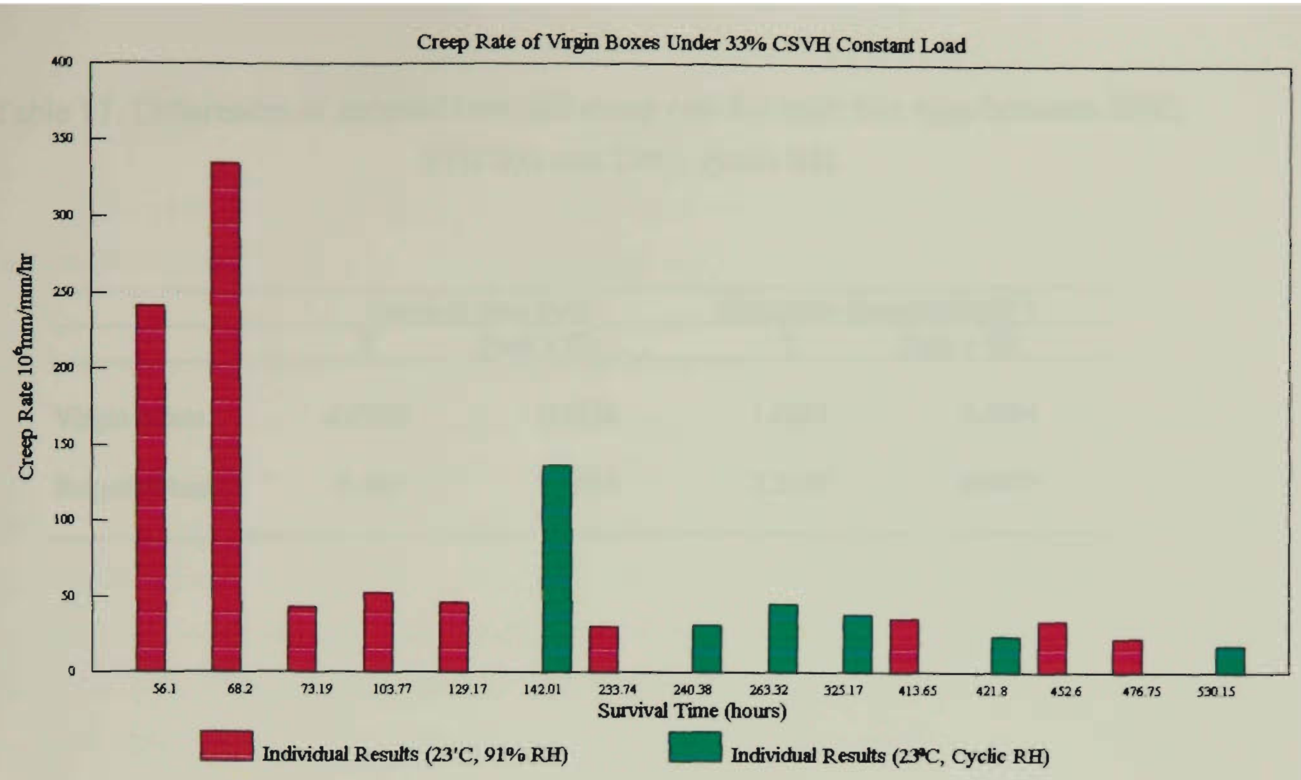


Figure 28a. Creep rate of boxes under 33% CSVH constant load

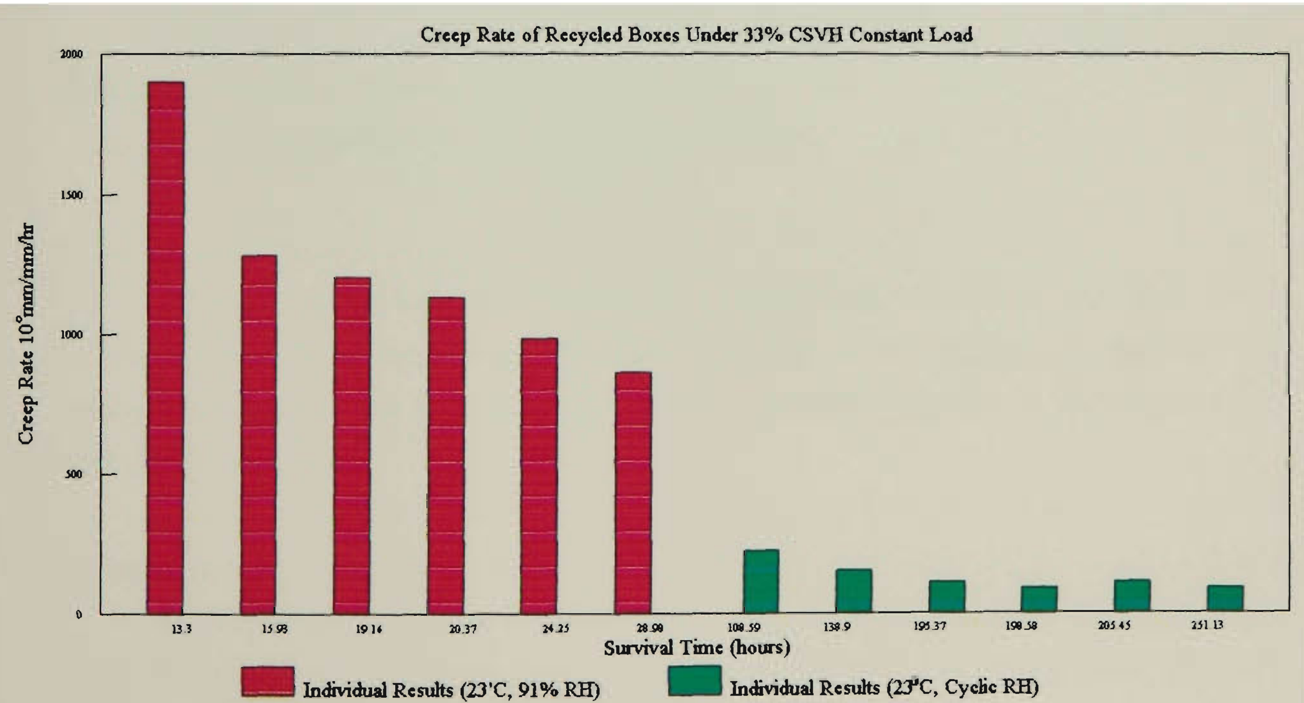


Figure 28b. Creep rate of boxes under 33% CSVH constant load

Table 17. Differences in survival time and creep rate for each box type between 23°C, 91% RH and 23°C, cyclic RH

	Survival time (hrs)		Creep rate (mm/mm/hr10^6)	
	T	Prob > |T|	T	Prob > |T|
Virgin boxes	-0.5621	0.5836	1.0651	0.3094
Recycled boxes	-7.762	0.0005	7.3185	0.0007

6.3.4 Factors affecting test results

Several authors have reported that creep data were scattered. In this study, creep data also exhibited great variation. The main factors which affected the results in this study were:

- Variation in the compression strength of the boxes

The boxes used in this study had a varying compression strength because of the process of fabricating. For example, the compression strength of virgin boxes is 2904N in 91% RH, (standard deviation 174.23). If we cover 95% of the cases, the compression strength would be 2904 $\pm 2\sigma$ N (2556N to 3252 N). So, a 33% of the average compression strength of virgin boxes would distribute from 29% to 37% of actual compression strength in a particular box, and this in turn could mean the difference between 2.5 and 14 days survival time.

- Uniformity of the adhesive between medium and liners

Uniformity is another factor which greatly affects the results. Even though we have carried out glue bond control, the actual glue bond strength was variable. The weakness in the adhesive bond tends to give way under stress and greatly accelerates the time to failure.

- Consistent stability of the environmental chamber

The errors of humidities in cyclic RH were $\pm 3\%$ RH.

- Predicted points

Because testing time was limited, predicted points were used. However, these predicted points are also affected by other variables such as maximum strain and the accuracy of regression line obtained from the secondary region, in the strain versus survival time curve.

- Sample size

Due to limited time, the sample size used in this study was only for a significant level α = 0.05 and power β = 0.9. However, the larger the sample size, the more accurate the results.

7.0 SUMMARY AND CONCLUSIONS

The compression strength and the compressive creep behavior of virgin and recycled regular slotted containers subjected to high and cyclic humidity were examined. Several conclusions can be drawn from this work:

1. Virgin boxes have a higher compression strength than recycled boxes after exposure to high (23°C, 91% RH) and cyclic (23°C, 91%-70%-91%) humidities.

2. Recycled boxes experienced greater loss in compression strength than virgin boxes after exposure to high and cyclic humidity.

3. Cyclic relative humidity conditioning caused significant reduction in compression strength for both box types, when compared to constant high humidity conditions.

4. Compression strength is not only related to final moisture content but also related to moisture history.

5. At 91% RH, creep strains were not significantly different between the two box types. The exception was at a deadload of 40% of the box compression strength of virgin boxes at 91% RH. In cyclic RH, creep strains were not significantly different when deadloads were above 55% of the compression strength of virgin boxes at cyclic RH.

6. Virgin and recycled boxes produced different survival times and creep rates under the same load levels and proportional load levels. The difference is statistically significant at all levels except around the 40%-55% deadload levels.

7. Virgin and recycled boxes performed differently in strain and survival time under the same load level of 33% of the box compression strength of virgin boxes at 91% RH and proportional load level of 80% of the box compression strength of virgin and recycled boxes at cyclic RH. Under other test conditions the differences were not significant.

8. There is a reasonable relationship between constant load and the logarithm of survival time. The equations used to predict survival times are shown in Section 6.3.2.3.

9. Due to the different precondition environment used in this investigation, it is still not certain that Caulfield's theory is valid for boxes. Thus this is an area in which more research would be justified.

10. Creep rate is a good predictor of survival time, the equations developed in this study are given in Section 6.3.2.5.

11. Creep rates of virgin boxes were not significantly different between 91% RH and cyclic RH.

12. Creep rates of recycled boxes were higher at 91% constant RH than in cyclic RH. This means recycled boxes last longer in cyclic RH than in 91% constant RH.

13. Recycled boxes had a lower moisture absorbtion rate than virgin boxes so that they can last longer than virgin boxes over a short period of high humidity.

14. The tests conducted in this study show that the acceptable load level for predicting survival time of virgin and recycled boxes and distinguishing the difference on creep performance between virgin and recycled boxes is less than 40% of the box compression strength measured at either 23°C, 91% RH or 23°C, cyclic RH conditions.

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9.0 APPENDICES

Appendix A

An analysis of variance for 2-factor factorial experiment for compression strength

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
MATERIAL	2	REC VIR
HUMIDITY	3	50% 91% CYCLIC

Number of observations in data set = 120

Dependent Variable: Compression Strength

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	194677481.7	38935496.3	1702.36	0.0001
Error	114	2607347.5	22871.5		
Corrected Total	119	197284829.2			

R-Square	C.V.	Root MSE	Com Strength Mean
0.986784	4.301998	151.2332	3515.41667

Source	DF	Anova SS	Mean Square	F Value	Pr > F
MATERIALS	1	363000.0	363000.0	15.87	0.0001
HUMIDITY	2	191594301.7	95797150.8	4188.50	0.0001
MATERIAL*HUMIDITY	2	2720180.0	1360090.0	59.47	0.0001

Appendix B

Results of 3 and 4 point stiffness of the box materials

3 point stiffness testing summary

			VIRGIN BOARD	RECYCLED BOARD
LOAD	(S/H)	MD	18.44	20.44
		CD	26.54	26.06
(N)	(H/H)	MD	7.45	7.36
		CD	8.29	7.21
DEF	(S/H)	MD	3.46	3.69
		CD	10.68	14.02
(mm)	(H/H)	MD	3.40	4.77
		CD	12.95	15.72
FACING STRENGTH	(S/H)	MD	3.14	3.43
		CD	4.52	4.38
	(H/H)	MD	1.27	1.24
(KN/m)		CD	1.41	1.21
STIFFNESS (50%MAXLOAD	(S/H)	MD	5.84	6.11
		CD	2.87	2.27
	(H/H)	MD	2.47	1.83
(N/mm)		CD	0.79	0.57
STIFFNESS (INITIAL)	(S/H)	MD	3.87	3.90
		CD	2.55	2.53
	(H/H)	MD	1.96	1.07
(N/mm)		CD	0.99	0.73
STIFFNESS (BENDING)	(S/H)	MD	12.96	13.59
		CD	6.40	5.06
	(H/H)	MD	5.50	4.08
(Nm)		CD	1.75	1.28

Note: 1. An avage of 10 test samples
2. S/H: Standard humidity (23°C,50%)
H/H: High humidity (23°C, 91%)

4 point stiffness testing summary

			VIRGIN BOARD	RECYCLED BOARD
LOAD	(S/H)	MD	4.99	4.98
		CD	3.68	3.20
(N)	(H/H)	MD	4.67	3.81
		CD	1.83	1.32
DEF	(S/H)	MD	196	172
		CD	301	301
(um)	(H/H)	MD	301	301
		CD	301	301
FACING STRENGTH	(S/H)	MD	0.85	0.84
		CD	0.62	0.54
	(H/H)	MD	0.79	0.64
(KN/m)		CD	0.31	0.22
STIFFNESS (50%MAXLOAD)	(S/H)	MD	24.27	27.47
		CD	11.31	9.95
	(H/H)	MD	14.81	11.94
(N/mm)		CD	5.31	3.50
STIFFNESS (BENDING)	(S/H)	MD	17.49	19.80
		CD	8.16	7.16
	(H/H)	MD	10.68	8.62
(Nm)		CD	3.82	2.52

Note: 1. An average of 10 test samples

2. S/H: Standard humidity (23°C,50%)

H/H: High humidity (23°C, 91%)

Appendix C

A t-test analysis for determining significance of the difference in initial compression strength (23°C, 50% RH) between virgin and recycled boxes

Variable: Compression Strength

MATERIAL	N	Mean	Std Dev	Std Error
REC	20	5439.50000000	172.82406631	38.64463604
VIR	20	5142.50000000	150.66082507	33.68878464

Variances	T	DF	Prob>|T|
Unequal	5.7932	37.3	0.0001
Equal	5.7932	38.0	0.0000

For H0: Variances are equal, F' = 1.32 DF = (19,19) Prob>F' = 0.5555

Appendix D

A t-test analysis for determining the significance of the difference in strength loss between virgin and recycled boxes

$$t=\frac{\Delta s-\Delta c}{\sqrt{v(\Delta s-\Delta c)}}$$

$$v(\Delta s-\Delta c)=[v(\Delta s)-v(\Delta c)]$$

$v(\Delta s)$ --(standard error of compression strength at Appita condition)^2

$v(\Delta c)$ --(standard error of compression strength after high or cyclic condition)^2

Δs -- Difference of initial compression strength = Y_{a1}-Y_{a2}
Δc -- Difference of compression strength after high or cyclic condition = Y_{b1}-Y_{b2}

Y_{a1} --Average compression strength of the virgin box at Appita condition
Y_{a2} --Average compression strength of the recycled box at Appita condition
Y_{b1} --Average compression strength of the virgin box after high or cyclic condition
Y_{b2} --Average compression strength of the recycled box after high or cyclic condition

23 C, 91% RH
Variable: Compression Strength

HUMIDITY	N	Mean	Std Dev	Std Error
50%	20	-297.00000000	244.83291832	54.74630485
91%	20	205.00000000	170.44060549	38.11167800

Variances	T	DF	Prob>|T|
Unequal	-7.5256	33.9	0.0001
Equal	-7.5256	38.0	0.0000

For H0: Variances are equal, F' = 2.06 DF = (19,19) Prob>F' = 0.1231

23 C, CYCLIC RH
Variable: Strength

HUMIDITY	N	Mean	Std Dev	Std Error
50%	20	-297.00000000	244.83291832	54.74630485
CYCLIC	20	422.00000000	199.44264444	44.59673106

Variances	T	DF	Prob>|T|
Unequal	-10.1824	36.5	0.0001
Equal	-10.1824	38.0	0.0000

For H0: Variances are equal, F' = 1.51 DF = (19,19) Prob>F' = 0.3794

Appendix E

Compression test summary

Compression strength and deflection values for virgin boxes (23°C, 50% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNI (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	5350	12.7	166.7	753.4	955.4
2	4780	11.4	118.7	842.1	993.4
3	5115	13.2	111.5	932.2	1250.0
4	5155	11.2	159.8	618.0	980.8
5	5040	11.3	118.3	789.5	910.7
6	5035	11.6	157.1	769.2	938.6
7	5040	11.3	140.6	819.7	1000.0
8	5380	12.0	154.1	647.1	980.8
9	5225	11.7	128.8	723.7	1083.3
10	5175	10.8	157.1	614.8	1115.4
11	5180	11.2	154.1	718.3	1020.0
12	5260	12.0	72.8	620.3	1000.0
13	5405	11.8	131.6	661.4	903.6
14	5080	11.0	153.3	604.8	925.9
15	5220	11.3	149.5	753.6	962.3
16	5265	10.8	173.1	649.6	1061.2
17	5030	12.6	107.3	649.4	944.4
18	5095	11.5	132.2	637.5	877.2
19	5010	11.5	146.1	781.3	1017.9
20	5010	10.6	140.0	750.0	974.0
MEAN VALUE	5143	11.6	138.6	716.8	994.7
STDS	151	0.7	24.1	90.0	84.7
VARS	22699	0.5	580.5	8106.3	7170.3

Compression strength and deflection values for recycled boxes (23°C, 50% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNI (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	5480	11.1	120.8	825.0	1020.4
2	5470	11.2	117.3	932.2	1085.1
3	5195	11.4	126.3	753.4	818.2
4	5545	10.1	115.8	879.6	1238.1
5	5565	10.3	119.4	942.9	1133.3
6	5660	10.8	123.6	911.0	1615.4
7	5590	10.9	131.0	785.7	1061.2
8	5470	10.6	129.9	733.3	961.5
9	5560	10.5	157.9	750.0	1098.6
10	5445	10.8	115.2	714.3	1060.0
11	5650	10.9	167.6	792.2	1085.1
12	5440	10.8	130.4	705.9	981.1
13	5110	10.5	112.6	726.9	1780.3
14	5080	10.7	121.1	800.0	847.5
15	5315	11.3	111.7	690.4	1039.2
16	5540	10.8	123.5	837.6	925.9
17	5495	10.6	136.2	657.4	1243.9
18	5445	10.9	159.9	825.0	961.5
19	5555	11.2	111.4	722.9	1108.7
20	5180	10.6	92.2	796.9	859.6
MEAN VALUE	5440	10.8	126.2	789.1	1096.2
STDS	173	0.3	18.1	81.5	236.9
VARS	29868	0.1	326.5	6636.0	56130.6

Compression strength and deflection values for virgin boxes (23°C, 91% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNI (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	2940	11.3	85.6	407.0	470.2
2	3195	15.3	97.3	423.5	495.3
3	2765	11.5	81.3	352.9	427.3
4	2990	11.0	99.8	458.5	480.8
5	2800	10.9	124.3	445.5	481.1
6	2860	14.7	94.5	313.6	538.7
7	3090	10.8	112.5	316.3	530.0
8	3070	11.1	86.9	329.7	612.2
9	3055	11.1	105.8	364.6	479.2
10	2865	10.3	120.3	430.8	541.9
11	3050	10.7	91.2	340.9	579.2
12	2640	11.3	73.1	360.6	493.4
13	2615	9.9	90.9	352.9	488.6
14	2895	11.1	87.4	389.6	584.2
15	3155	11.4	90.1	384.6	508.5
16	2855	14.7	72.6	344.8	374.1
17	3070	11.6	89.3	393.0	483.9
18	2685	11.1	97.5	312.5	423.7
19	2735	11.9	95.4	411.0	442.5
20	2760	10.6	92.4	298.0	448.3
MEAN VALUE	2905	11.6	94.4	371.5	494.2
STDS	174	1.5	13.4	47.3	58.5
VARS	30355	2.2	180.3	2241.3	3417.5

Compression strength and deflection values for recycled boxes (23°C, 91% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNI (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	2735	9.8	79.8	463.9	508.5
2	2770	10.1	44.9	548.8	552.3
3	2780	10.3	74.4	430.6	469.0
4	2710	9.7	85.6	447.1	459.5
5	2775	9.6	86.0	387.9	479.2
6	2745	9.3	89.6	428.6	470.2
7	2735	9.1	95.5	538.9	547.4
8	2780	9.2	99.0	494.5	488.6
9	2595	9.6	77.4	414.4	454.5
10	2605	9.3	95.9	430.6	439.9
11	2570	9.6	84.2	400.0	404.3
12	2555	9.3	91.9	433.5	454.5
13	2690	9.5	84.7	493.4	490.2
14	2725	9.2	91.9	473.7	530.0
15	2725	10.1	71.2	409.1	428.6
16	2655	9.6	92.4	502.8	500.0
17	2805	9.7	85.6	511.4	513.7
18	2715	9.8	101.2	424.5	546.4
19	2600	9.8	80.2	443.8	432.3
20	2720	9.9	82.8	494.5	498.3
MEAN VALUE	2700	9.6	84.7	458.6	483.4
STDS	76	0.3	12.3	46.4	42.0
VARS	5837	0.1	151.7	2148.4	1763.5

Compression strength and deflection values for virgin boxes
(23°C, 91%-70%-91% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNESS (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	2785	10.1	95.4	460.4	485.7
2	2655	10.4	78.9	328.9	483.9
3	2665	10.2	97.5	416.7	450.5
4	2785	11.0	90.5	361.4	540.8
5	2660	10.5	93.8	280.4	480.8
6	2665	10.4	104.3	348.8	430.9
7	2725	9.8	103.8	340.9	442.5
8	2595	11.7	91.9	329.5	400.0
9	2540	12.1	69.1	352.9	439.4
10	2520	11.0	66.7	294.1	392.3
11	2735	9.4	114.2	340.9	495.3
12	2530	10.5	87.0	348.8	442.5
13	2775	10.9	101.1	321.4	439.9
14	2875	11.0	79.6	375.0	535.4
15	2390	9.3	90.5	384.6	463.0
16	2650	9.8	106.5	357.1	431.0
17	2475	11.0	77.0	376.8	449.1
18	2925	13.0	82.2	340.9	592.9
19	2555	10.4	94.4	362.3	428.6
20	2780	10.5	107.9	365.9	455.9
MEAN VALUE	2664	10.6	91.6	354.4	464.0
STDS	137	0.9	13.0	39.3	48.7
VARS	18856	0.8	169.3	1541.6	2368.2

Compression strength and deflection values for recycled boxes
(23℃, 91%-70%-91% RH)

SPECIMEN NO	LOAD (N)	DEF. (mm)	INITIAL STIFFNESS (N/mm)	STIFF @ 50% (N/mm)	MAX. STIFFNESS (N/mm)
1	2540	8.9	87.8	405.4	406.5
2	1985	8.7	90.0	324.7	355.5
3	2460	8.9	101.5	306.1	362.3
4	2360	9.2	93.7	352.1	387.6
5	2450	8.1	107.1	361.4	431.0
6	2075	8.3	101.5	294.1	326.8
7	2145	8.4	101.3	328.9	344.6
8	2000	8.8	95.6	289.6	344.7
9	2335	8.5	102.3	337.1	354.6
10	2265	8.4	92.2	365.9	472.4
11	2295	8.6	99.7	316.5	403.1
12	2040	8.4	66.3	317.8	395.1
13	2380	8.4	110.3	406.3	414.6
14	2350	8.5	110.0	320.5	370.6
15	2370	9.2	103.7	396.8	393.7
16	2320	8.6	100.1	347.2	414.6
17	2000	8.5	68.6	327.9	352.1
18	2045	8.6	104.0	283.8	335.6
19	2180	8.3	111.2	347.2	363.2
20	2250	8.6	102.6	339.0	348.0
MEAN VALUE	2227	8.6	98.0	334.9	377.4
STDS	161	0.3	12.2	32.8	37.6
VARS	26075	0.1	149.7	1077.6	1413.4

Appendix F

Moisture contents of boxes in compression tests

Moisture contents of virgin boxes (23°C, 50% RH)

SAMPLE NO.	1	2	3	4
CAN NO.	5	17	26	25
1 st WT. (g)	120.6	119.3	119.4	122.5
2 nd Wt. (g)	119.5	118.3	118.5	121.4
CAN WT. (g)	106.1	106.6	107.2	108.0
MOISTURE CONTENT	7.7%	7.8%	7.9%	7.9%

AVERAGE	7.8%
STDS	0.1%

Moisture contents of recycled boxes (23°C, 50% RH)

SAMPLE NO.	1	2	3	4
CAN NO.	35	12	54	21
1 st WT. (g)	123.3	128.2	123.3	119.2
2 nd Wt. (g)	122.3	126.6	122.0	118.3
CAN WT. (g)	108.5	107.2	105.9	107.5
MOISTURE CONTENT	7.1%	7.4%	7.5%	7.5%

AVERAGE	7.4%
STDS	0.2%

Moisure contents of virgin boxes (23°C, 91% RH)

SAMPLE NO.	1	2	3	4	5	6	7	8	9	10
BOX NO.	168	20	45	205	9	105	94	300	188	3
CAN NO.	17	18	23	27	6	38	30	29	54	28
1 st WT. (g)	116.3	117.6	119.4	118.9	116.6	118.6	117.7	120.9	117.00	117.22
2 nd Wt. (g)	114.9	116.0	117.7	117.2	115.0	117.0	116.2	119.1	115.40	115.63
CAN WT. (g)	106.6	107.5	107.6	107.2	105.9	107.4	107.5	108.7	105.86	106.26
MOISTURE CONTENT	14.7%	15.7%	14.8%	14.6%	14.6%	14.3%	14.4%	14.8%	14.4%	14.5%

AVERAGE 14.7%

STDS 0.4%

Moisture contents of recycled boxes (23°C, 91% RH)

SAMPLE NO.	1	2	3	4	5	6	7	8	9	10
BOX NO.	245	29	94	278	188	316	38	105	168	45
CAN NO.	46	21	12	13	4	7	34	60	19	25
1 st WT. (g)	121.5	123.8	119.6	120.2	120.3	120.9	120.6	119.6	119.3	120.4
2 nd Wt. (g)	119.6	121.6	117.9	118.4	118.5	118.9	118.7	117.9	117.7	118.6
CAN WT. (g)	108.1	107.6	107.3	107.5	107.1	106.8	106.9	107.4	108.0	108.0
MOISTURE CONTENT	13.9%	13.8%	13.9%	13.9%	13.8%	14.3%	13.5%	13.6%	14.1%	14.4%

AVERAGE 13.9%

STDS 0.3%

VARS 0.00%

Moisture contents of virgin boxes (23°C, 91%-70%-91% RH)

SAMPLE NO.	1	2	3	4	5	6	7	8	9
CAN NO.	6	53	32	23	25	29	31	7	19
1 st WT. (g)	118.8	120.1	125.3	123.8	123.2	122.7	122.2	121.1	121.4
2 nd Wt. (g)	117.0	118.3	122.7	121.5	120.9	120.7	120.1	118.9	119.5
CAN WT. (g)	105.9	107.9	107.1	107.6	107.5	108.7	108.5	106.5	108.0
MOISTURE CONTENT	14.5%	14.5%	14.2%	14.1%	14.4%	14.3%	14.7%	14.7%	14.3%

Note: Boxes were taken out from conditioning room at 91% RH.

AVERAGE	14.4%
STDS	0.2%

Moisture contents of recycled boxes (23°C, 91%-70%-91% RH)

SAMPLE NO.	1	2	3	4	5	6	7	8	9
CAN NO.	35	34	38	4	3	21	40	17	52
1 st WT. (g)	118.6	120.7	121.3	129.9	123.8	123.1	126.7	122.5	124.1
2 nd Wt. (g)	117.2	118.9	119.4	126.8	121.4	120.8	124.0	120.2	121.6
CAN WT. (g)	108.4	107.5	107.5	107.0	106.5	107.3	107.9	106.6	107.0
MOISTURE CONTENT	13.8%	13.8%	13.9%	13.6%	14.0%	14.0%	14.1%	14.1%	14.3%

Note: Boxes were taken out from conditioning room at 91% RH.

AVERAGE	14.0%
STDS	0.2%

Appendix G

A t-test analysis for determining the significance of the difference in final compression strength (at both 91% & cyclic RH) between virgin and recycled boxes

<u>23 C, 91% RH</u>

Variable: Compression Strength

MATERIAL	N	Mean	Std Dev	Std Error
REC	20	2699.50000000	76.39750616	17.08300171
VIR	20	2904.50000000	174.22686360	38.95831105

Variances	T	DF	Prob>|T|
Unequal	-4.8191	26.0	0.0001
Equal	-4.8191	38.0	0.0000

For H0: Variances are equal, F' = 5.20 DF = (19,19) Prob>F' = 0.0007

<u>23 C, CYCLIC RH</u>

Variable: Compression Strength

MATERIAL	N	Mean	Std Dev	Std Error
REC	20	2242.25000000	172.08837234	38.48012987
VIR	20	2664.25000000	137.31710324	30.70503773

Variances	T	DF	Prob>|T|
Unequal	-8.5721	36.2	0.0001
Equal	-8.5721	38.0	0.0000

For H0: Variances are equal, F' = 1.57 DF = (19,19) Prob>F' = 0.3335

Appendix H

A t-test analysis for determining significance of the difference in the compression for each box type between 23°C, 50% RH and 23°C, cyclic RH.

Virgin boxes:

Variable: Strength

HUMIDITY	N	Mean	Std Dev	Std Error
91%	20	2901.95000000	171.72422047	38.39870303
CYCLIC	20	2664.25000000	137.31710324	30.70503773

Variances	T	DF	Prob>|T|
Unequal	4.8347	36.2	0.0001
Equal	4.8347	38.0	0.0000

For H0: Variances are equal, F' = 1.56 DF = (19,19) Prob>F' = 0.3381

Recycled boxes:

Variable: Strength

HUMIDITY	N	Mean	Std Dev	Std Error
91%	20	2699.50000000	76.39750616	17.08300171
CYCLIC	20	2242.25000000	172.08837234	38.48012987

Variances	T	DF	Prob>|T|
Unequal	10.8606	26.2	0.0001
Equal	10.8606	38.0	0.0000

For H0: Variances are equal, F' = 5.07 DF = (19,19) Prob>F' = 0.0009

Appendix I

A t-test analysis for determining significance of the difference in moisture contents for each box type between 23°C, 50% RH and 23°C, cyclic RH.

Virgin boxes:

Variable: Moisture Contents

HUMIDITY	N	Mean	Std Dev	Std Error
91%	10	14.68300000	0.39880516	0.12611326
CYCLIC	9	14.43555556	0.22428281	0.07476094

Variances	T	DF	Prob>|T|
Unequal	1.6878	14.4	0.1130
Equal	1.6397	17.0	0.1194

For H0: Variances are equal, F' = 3.16 DF = (9,8) Prob>F' = 0.1196

Recycled boxes:

Variable: Moisture Contents

HUMIDITY	N	Mean	Std Dev	Std Error
91%	10	13.92700000	0.28503606	0.09013632
CYCLIC	9	13.97555556	0.20439613	0.06813204

Variances	T	DF	Prob>|T|
Unequal	-0.4297	16.3	0.6730
Equal	-0.4221	17.0	0.6782

For H0: Variances are equal, F' = 1.94 DF = (9,8) Prob>F' = 0.3617

Appendix J

An analysis of variance for 3-factor factorial experiment for creep strain survival time and creep rate

Class Level Information

Class	Levels	Values
MATERIAL	2	REC VIR
HUMIDITY	2	91% CYC
DEADLOAD	3	55% 70% 80%

Number of observations in data set = 69

Dependent Variable: Creeprate

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	8688438096	789858009	45.96	0.0001
Error	57	979635878	17186594		
Corrected Total	68	9668073974			

R-Square	C.V.	Root MSE	CREEPRATE Mean
0.898673	36.30877	4145.672	11417.8261

Source	DF	Anova SS	Mean Square	F Value	P> F
MATERIAL	1	238807848	238807848	13.90	0.0004
HUMIDITY	1	1942056318	1942056318	113.00	0.0001
DEADLOAD	2	5249973433	2624986716	152.73	0.0001
MATERIAL*HUMIDITY	1	139904975	139904975	8.14	0.0060
MTERIAL*DEADLOAD	2	224639900	112319950	6.54	0.0028
HUMIDITY*DEADLOAD	2	625802431	312901216	18.21	0.0001
MATERI*HUMIDI*DEADLO	2	267253190	133626595	7.78	0.0010

Appendix K

The t-test analyses for determining significance of the difference in creep strain at high and cyclic RH between virgin and recycled boxes under different constant loads

23 C, 91% RH

A t-test Analysis for determining significance of the difference in creep strain, at 23° C, 91% RH between virgin and recycled boxes under 40%CSVH constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	4.29833333	0.18914721	0.07721902
VIR	9	4.69555556	0.23633192	0.07877731

Variances	T	DF	Prob>|T|
Unequal	-3.6009	12.4	0.0035
Equal	-3.4354	13.0	0.0044

For H0: Variances are equal, F' = 1.56 DF = (8,5) Prob>F' = 0.6473

A t-test Analysis for determining significance of the difference in creep strain at 23° C, 91% RH between virgin and recycled boxes under 55%CSVH constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	4.65500000	0.38697545	0.15798207
VIR	6	4.55000000	0.40373258	0.16482314

Variances	T	DF	Prob>|T|
Unequal	0.4599	10.0	0.6554
Equal	0.4599	10.0	0.6554

For H0: Variances are equal, F' = 1.09 DF = (5,5) Prob>F' = 0.9281

A t-test Analysis for determining significance of the difference in creep strain at 23° C, 91% RH between virgin and recycled boxes under 70%CSVH constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	4.56833333	0.35301086	0.14411608
VIR	6	4.65000000	0.55407581	0.22620050

Variances	T	DF	Prob>|T|
Unequal	-0.3045	8.5	0.7681
Equal	-0.3045	10.0	0.7670

For H0: Variances are equal, F' = 2.46   DF = (5,5)   Prob>F' = 0.3449

A t-test Analysis for determining significance of the difference in creep strain at 23° C, 91% RH between virgin and recycled boxes under 80%CSVH constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	4.72166667	0.24742002	0.10100880
VIR	6	4.55500000	0.60278520	0.24608603

Variances	T	DF	Prob>|T|
Unequal	0.6265	6.6	0.5520
Equal	0.6265	10.0	0.5450

For H0: Variances are equal, F' = 5.94   DF = (5,5)   Prob>F' = 0.0729

23 C, CYCLIC RH

A t-test Analysis for determining significance of the difference in creep strain at 23° C, cyclic RH between virgin and recycled boxes under 55%CSVC constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	3.81333333	0.25319294	0.10336559
VIR	6	3.97166667	0.31625412	0.12911020

Variances	T	DF	Prob>|T|
Unequal	-0.9573	9.5	0.3621
Equal	-0.9573	10.0	0.3610

For H0: Variances are equal, F' = 1.56 DF = (5,5) Prob>F' = 0.6374

A t-test Analysis for determining significance of the difference in creep strain, survival time, t 23° C, cyclic RH between virgin and recycled boxes under 70%CSVC constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	4	4.61000000	0.27349589	0.13674794
VIR	4	4.69250000	0.65127439	0.32563720

Variances	T	DF	Prob>|T|
Unequal	-0.2336	4.0	0.8267
Equal	-0.2336	6.0	0.8231

For H0: Variances are equal, F' = 5.67 DF = (3,3) Prob>F' = 0.1880

A t-test Analysis for determining significance of the difference in creep strain at 23° C, cyclic RH between virgin and recycled boxes under 80%CSVC constant load

Variable: Strain

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	4.40333333	0.48458917	0.19783270
VIR	6	4.70666667	0.26135544	0.10669791

Variances	T	DF	Prob>|T|
Unequal	-1.3495	7.7	0.2157
Equal	-1.3495	10.0	0.2069

For H0: Variances are equal, F' = 3.44 DF = (5,5) Prob>F' = 0.2015

Appendix L

The t-test analyses for determining significance of the difference in survival time at high and cyclic RH between virgin and recycled boxes under different constant loads

<u>23C, 91% RH</u>

A t-test Analysis for determining significance of the difference in survival time at 23° C, 91% RH between virgin and recycled boxes under 33%CSVC constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	20.33166667	5.66286647	2.31185556
VIR	9	257.95888889	245.74772351	81.91590784

Variances	T	DF	Prob>|T|
Unequal	-2.8997	8.0	0.0199
Equal	-2.3384	13.0	0.0360

For H0: Variances are equal, F' = 1883.24 DF = (8,5) Prob>F' = 0.0000

A t-test Analysis for determining significance of the difference in survival time at 23° C, 91% RH between virgin and recycled boxes under 40%CSVH constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	14.04166667	2.19534432	0.89624556
VIR	9	17.18333333	7.72773253	2.57591084

Variances	T	DF	Prob>|T|
Unequal	-1.1519	9.8	0.2767
Equal	-0.9594	13.0	0.3549

For H0: Variances are equal, F' = 12.39 DF = (8,5) Prob>F' = 0.0131

A t-test Analysis for determining significance of the difference in survival time at 23° C, 91% RH between virgin and recycled boxes under 55%CSVH constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	3.46500000	0.27075819	0.11053657
VIR	6	3.04833333	0.48267657	0.19705188

Variances	T	DF	Prob>|T|
Unequal	1.8442	7.9	0.1031
Equal	1.8442	10.0	0.0949

For H0: Variances are equal, F' = 3.18 DF = (5,5) Prob>F' = 0.2302

A t-test Analysis for determining significance of the difference in survival time at 23° C, 91% RH between virgin and recycled boxes under 70%CSVH constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	1.62333333	0.31411251	0.12823589
VIR	6	1.24666667	0.16305418	0.06656659

Variances	T	DF	Prob>|T|
Unequal	2.6070	7.5	0.0331
Equal	2.6070	10.0	0.0262

For H0: Variances are equal, F' = 3.71 DF = (5,5) Prob>F' = 0.1764

A t-test Analysis for determining significance of the difference in survival time at 23° C, 91% RH between virgin and recycled boxes under 80%CSVH constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	0.78000000	0.20784610	0.08485281
VIR	6	0.57833333	0.10284292	0.04198545

Variances	T	DF	Prob>|T|
Unequal	2.1302	7.3	0.0691
Equal	2.1302	10.0	0.0590

For H0: Variances are equal, F' = 4.08 DF = (5,5) Prob>F' = 0.1487

23 C, CYCLIC RH

A t-test Analysis for determining significance of the difference in survival time at 23° C, cyclic RH between virgin and recycled boxes under 33%CSVH constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	183.01333333	51.02513368	20.83092359
VIR	6	320.47166667	138.40813812	56.50488577

Variances	T	DF	Prob>|T|
Unequal	-2.2825	6.3	0.0605
Equal	-2.2825	10.0	0.0456

For H0: Variances are equal, F' = 7.36 DF = (5,5) Prob>F' = 0.0471

A t-test Analysis for determining significance of the difference in survival time at 23° C, cyclic RH between virgin and recycled boxes under 55%CSVC constant loads

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	20.50000000	1.94319325	0.79330532
VIR	6	22.14166667	1.27687770	0.52128314

Variances	T	DF	Prob>|T|
Unequal	-1.7294	8.6	0.1193
Equal	-1.7294	10.0	0.1144

For H0: Variances are equal, F' = 2.32 DF = (5,5) Prob>F' = 0.3780

A t-test Analysis for determining significance of the difference in survival time at 23° C, cyclic RH between virgin and recycled boxes under 70%CSVC constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	4	16.16250000	0.84001488	0.42000744
VIR	4	8.55750000	7.79402068	3.89701034

Variances	T	DF	Prob>|T|
Unequal	1.9403	3.1	0.1460
Equal	1.9403	6.0	0.1004

For H0: Variances are equal, F' = 86.09 DF = (3,3) Prob>F' = 0.0042

A t-test Analysis for determining significance of the difference in survival time at 23° C, cyclic RH between virgin and recycled boxes under 80%CSVC constant load

Variable: Time

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	1.30083333	0.32961215	0.13456360
VIR	6	1.13733333	0.45160499	0.18436696

Variances	T	DF	Prob>|T|
Unequal	0.7163	9.1	0.4917
Equal	0.7163	10.0	0.4902

For H0: Variances are equal, F' = 1.88 DF = (5,5) Prob>F' = 0.5061

Appendix M

The t-test analyses for determining significance of the difference in creep rate at high and cyclic RH between virgin and recycled boxes under different constant load

23 C, 91% RH

A t-test Analysis for determining significance of the difference in creep rate at 23° C, 91% RH between virgin and recycled boxes under 33%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	1225.00000000	363.74441576	148.49803590
VIR	9	93.32555556	113.16953445	37.72317815

Variances	T	DF	Prob>|T|
Unequal	7.3862	5.7	0.0005
Equal	8.8572	13.0	0.0000

For H0: Variances are equal, F' = 10.33 DF = (5,8) Prob>F' = 0.0049

A t-test Analysis for determining significance of the difference in creep rate at 23° C, 91% RH between virgin and recycled boxes under 40%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	1431.66666667	250.15328634	102.12465150
VIR	9	1140.00000000	527.04364146	175.68121382

Variances	T	DF	Prob>|T|
Unequal	1.4353	12.1	0.1765
Equal	1.2532	13.0	0.2322

For H0: Variances are equal, F' = 4.44 DF = (8,5) Prob>F' = 0.1174

A t-test Analysis for determining significance of the difference in creep rate at 23° C, 91% RH between virgin and recycled boxes under 55%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	5616.66666667	449.07311951	183.33333333
VIR	6	5316.66666667	1168.61741672	477.08606258

Variances	T	DF	Prob>|T|
Unequal	0.5870	6.4	0.5773
Equal	0.5870	10.0	0.5702

For H0: Variances are equal, F' = 6.77 DF = (5,5) Prob>F' = 0.0559

A t-test Analysis for determining significance of the difference in creep rate at 23° C, 91% RH between virgin and recycled boxes under 70%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	10350.00000000	1997.74873295	815.57750500
VIR	6	13616.66666667	5273.48714483	2152.89211166

Variances	T	DF	Prob>|T|
Unequal	-1.4189	6.4	0.2029
Equal	-1.4189	10.0	0.1863

A t-test Analysis for determining significance of the difference in creep rate at 23° C, 91% RH between virgin and recycled boxes under 80%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	23933.33333333	8748.86659326	3571.70983019
VIR	6	40150.00000000	7538.63382849	3077.63437291

Variances	T	DF	Prob>|T|
Unequal	-3.4396	9.8	0.0066
Equal	-3.4396	10.0	0.0063

For H0: Variances are equal, F' = 1.35 DF = (5,5) Prob>F' = 0.7518

23 C, CYCLIC RH

A t-test Analysis for determining significance of the difference in creep rate at 23° C, cyclic RH between virgin and recycled boxes under 33%CSVH constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	127.51000000	51.17067637	20.89034115
VIR	6	48.80333333	44.11151399	18.00845018

Variances	T	DF	Prob>|T|
Unequal	2.8537	9.8	0.0175
Equal	2.8537	10.0	0.0171

For H0: Variances are equal, F' = 1.35 DF = (5,5) Prob>F' = 0.7525

A t-test Analysis for determining significance of the difference in creep rate at 23° C, cyclic RH between virgin and recycled boxes under 55%CSVC constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	126.66666667	40.82482905	16.66666667
VIR	6	95.00000000	16.43167673	6.70820393

Variances	T	DF	Prob>|T|
Unequal	1.7626	6.6	0.1243
Equal	1.7626	10.0	0.1084

For H0: Variances are equal, F' = 6.17 DF = (5,5) Prob>F' = 0.0674

A t-test Analysis for determining significance of the difference in creep strain, survival time, and creep rate at 23° C, cyclic RH between virgin and recycled boxes under 70%CSVC constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	4	157.50000000	43.49329450	21.74664725
VIR	4	4302.50000000	4956.23092682	2478.11546341

Variances	T	DF	Prob>|T|
Unequal	-1.6726	3.0	0.1930
Equal	-1.6726	6.0	0.1454

For H0: Variances are equal, F' = 9999.99 DF = (3,3) Prob>F' = 0.0001

A t-test Analysis for determining significance of the difference in creep strain, survival time, and creep rate at 23° C, cyclic RH between virgin and recycled boxes under 80%CSVC constant load

Variable: Creeprate

MATERIAL	N	Mean	Std Dev	Std Error
REC	6	13873.33333333	2682.89147501	1095.28585817
VIR	6	14066.66666667	2444.55858319	997.98686253

Variances	T	DF	Prob>|T|
Unequal	-0.1305	9.9	0.8988
Equal	-0.1305	10.0	0.8988

For H0: Variances are equal, F' = 1.20 DF = (5,5) Prob>F' = 0.8432

Appendix N

A t-test analysis for determining significance of the difference in survival time, and creep rate for each box type under 33%CSVH constant load between 23°C,91% RH and 23°C, cyclic RH

Virgin boxes

Variable: Time

HUMIDITY	N	Mean	Std Dev	Std Error
91%	9	257.95888889	245.74772351	81.91590784
cyclic	6	320.47166667	138.40813812	56.50488577

Variances	T	DF	Prob>|T|
Unequal	-0.6282	12.8	0.5410
Equal	-0.5621	13.0	0.5836

For H0: Variances are equal, F' = 3.15 DF = (8,5) Prob>F' = 0.2215

Variable: Creeprate

HUMIDITY	N	Mean	Std Dev	Std Error
91%	9	93.32555556	113.16953445	37.72317815
cyclic	6	48.80333333	44.11151399	18.00845018

Variances	T	DF	Prob>|T|
Unequal	1.0651	11.1	0.3094
Equal	0.9093	13.0	0.3797

For H0: Variances are equal, F' = 6.58 DF = (8,5) Prob>F' = 0.0528

Recycled boxes

Variable: Time

HUMIDITY	N	Mean	Std Dev	Std Error
91%	6	20.33166667	5.66286647	2.31185556
cyclic	6	183.01333333	51.02513368	20.83092359

Variances	T	DF	Prob>|T|
Unequal	-7.7620	5.1	0.0005
Equal	-7.7620	10.0	0.0000

For H0: Variances are equal, F' = 81.19 DF = (5,5) Prob>F' = 0.0001

Variable: Creeprate

HUMIDITY	N	Mean	Std Dev	Std Error
91%	6	1225.00000000	363.74441576	148.49803590
cyclic	6	127.51000000	51.17067637	20.89034115

Variances	T	DF	Prob>|T|
Unequal	7.3185	5.2	0.0007
Equal	7.3185	10.0	0.0000

For H0: Variances are equal, F' = 50.53 DF = (5,5) Prob>F' = 0.0006