This is to certify that the

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PERFORMANCE OF RECYCLED CORRUGATED FIBERBOARD UNDER VARIOUS TEMPERATURES AND HUMIDITIES

presented by

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Gary Burgess
Major professor

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PERFORMANCE OF RECYCLED CORRUGATED FIBERBOARD UNDER VARIOUS TEMPERATURES AND HUMIDITIES

By

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ABSTRACT

PERFORMANCE OF RECYCLED CORRUGATED FIBERBOARD UNDER VARIOUS TEMPERATURES AND HUMIDITIES

By

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Strength properties of recycled corrugated board such as box compression strength, edge crush, flat crush, pin-adhesion, puncture resistance, and bursting strength were determined for various board recycled contents and humidity conditions. The moisture content of the conditioned recycled fiberboard under three temperatures and humidities was also determined. In addition, the box compression strength predicted by the Mckee formula was compared to the actual box compression strength.

The compression strength of the boxes and the strength properties of the recycled board itself were not found to decrease uniformly with moisture content as expected. This was due most likely to differences in manufacturing processes and the type of recycled fiber used. The moisture content of the recycled board was found to have a negative influence on edge crush, flat crush and pin-adhesion but a slightly positive influence on puncture and bursting strength.

Dedicated to

my parents, Chalaw and Nipa Thewasano

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INTRODUCTION

Recycling plays an important role in the packaging industry. Recycled plastics made from foam packaging are an example of an area where recycling has proven to be cost-effective. Corrugated fiberboard is another material which is used in packaging and is environmentally friendly. Corrugated fiberboard is biodegradable which means that it decomposes by biological means and therefore can be disposed of in a landfill (Anon, 1992: pg 25). The use of recycled fiber reduces the problem of the solid waste in landfills and also decreases the amount of virgin fiber needed (Kishbaugh, 1990: pg 27-28 and Uutela and Black, 1990: pg 50).

Due to the solid waste problem, the use of recycled board is supported by the government in terms of recycling laws. For example, some states in the U.S. and all government entities, including schools, are required to develop recycling programs for at least high-grade paper and corrugated cardboard (Glenn, 1992: pg 35-36). Solid waste management programs at the state level have been created to solve the solid waste problem. The paper industry is involved in recycling not only for the benefit of waste management but also by political command. About half the states in the U.S. have comprehensive laws on the books to increase recycling (Cartledge, 1991: pg 152, 154).

Corrugated fiberboard consists of a corrugating medium sandwiched in between two linerboards. The corrugating medium is the fluted or corrugated center of the board and the linerboard is the flat material outside. In the manufacture of corrugated cases, about two-thirds of the raw materials used consists of recycled fiber. This shows that the amount of recycled fiber is becoming the chief raw material used in the manufacturing process (Anon, 1982: pg 6). The trend is to incorporate more recycled fiber into both the liner and medium to satisfy consumer demands and recycling laws for environmentally friendly packaging (Kelsey, 1992: pg 18).

It is well known that the corrugated container plays an important role in protection. Its function is to restrain the product as it moves through the distribution system and to protect it from environmental hazards such as impact, vibration, compression, humidity and temperature. Moreover, its role is to reserve enough strength to support high compressive loads for long periods in warehouse storage, especially at high humidity. To fulfill these requirements, corrugated board must be fabricated to satisfy the requirements of Rule 41, Item 222 (Bever, 1986: pg 927-928).

There are several tests carried out by container makers on corrugated fiberboard containers to ensure that there is maximum protection provided for the least use of materials to avoid "over packaging" (Anon, 1992: pg 25). In the past, it was discovered that use of high-performance corrugated containers provided better stacking strength (Wallace, et al, 1991: pg 25-26). According to Boonyasarn's study (Boonyasarn, 1990: pg 1-68) on the effect of cyclic environments on the compression strength of boxes made from fiber-efficient corrugated fiberboard, boxes made from regular fiber-efficient linerboards experienced greater strength loss than the ones made from standard fiberboard after exposure to cyclic conditions while both fiberboard boxes performed similarly under non-cyclic environments. This was thought to be due to differences in moisture absorption between the two different box materials. The general trend was that compression strength decreased as the moisture content of the box material increased.

Although recycled fiber is still not as strong as virgin fiber, it has improved (Pels, 1991: pg 63-64). There are many problems associated with using recycled fiberboard. Recycled vegetable container boards for example are too weak to serve as fresh vegetable boxes, especially at high relative humidities (Anon, 1985: pg 13-14). The blend of recycled paper and virgin pulp also creates printing problems even if the printing is made by flexography which requires less pressure than other printing systems. Recycled fiber does not allow for fine detail: the more detail that is required, the more the flutes are damaged by the printing rollers, which then affects the strength of the finished corrugated box (Anon, 1987: pg 13).

Because containers are stacked as high as possible in warehouses, the compression force on the bottom box in the stack can be substantial. Compressing a box normally causes it to bulge outward which in turn causes the board to bend. Because the board bends, the outside and inside linerboards are stressed differently during stacking: the outside linerboard is in tension and the inside linerboard is in compression. Therefore, the percent of recycled pulp in both linerboards and the medium is important.

The purpose of this study is to evaluate the effect of recycled content and basis weight on the box compression strength, and the edge crush, flat crush, bursting, puncture strength, and pin-adhesion strengths of recycled corrugated fiberboard, and to compare performance when the boards have different moisture contents. A secondary objective is to compare the compression strength of boxes made from various recycled boards to each other and to calculated values based on prediction equations.

LITERATURE REVIEW

I. BOX COMPRESSION STRENGTH

The compression strength of a corrugated board box is an indicator of the stacking strength of corrugated board packages (Markstrom, 1988: pg 9). Since the shipping container encounters various environmental and handling hazards related to compression, it should satisfy the minimum requirements of Rule 41, item 222, so that box failure does not damage the product inside (Fibre Box Handbook Supplement, 1991: pg 8 and Maltenfort, 1988: pg 41). Due to an increase in the use of recycled materials, rule 41 has been changed to support recycled corrugated fiberboard by reducing the minimum requirement of performance. This includes reducing the amount of material by using lower weight, high-performance packages and decreasing the basis weight 10 to 20% on average to reduce over packaging.

According to ASTM D642-72 (revised 1983), the compression strength of a box is determined by placing the box at the center of the lower platen of a compression tester that is connected either to a load cell or to a mechanical scale. To ensure definite contact between the specimen and the platen, an initial pressure or preload of 50 lb is applied. The upper platen is then lowered onto the box at a continuous rate 0.5 in/min until the maximum load has been reached. The compression strength is defined to be the maximum load carried by the box.

Although the compression strength from the test can be used to predict package performance and strength, there are differences between actual performance and laboratory tests. The difference can be attributed to a number of different factors. Hand-made boxes for example will generally have higher compression strengths than production made boxes by up to 8% (Maltenfort, 1988: pg 271, 273).

Another factor which accounts for the difference between the laboratory and warehouse is that the environment for the former is usually 72°F and 50%RH and the latter is constantly changing. The weakening of the box is greatest under changing conditions when the container tries to equilibrate to new conditions under the load (Leake, 1988: pg 74-75).

Both temperature and humidity affect final box performance. This is because the corrugated fiberboard is made of paper and paper is composed of cellulose which absorbs moisture. The moisture content in turn is affected by the temperature (Back, 1989: pg 101). Normally, the moisture content of the liner or medium should be between 6% to 7%. Too much moisture weakens the board and lowers box compression strength. Moisture absorption by the adhesive at the interface between the linerboard and medium also affects the stacking performance of corrugated fiberboard (Byrd, 1986: pg 99).

The decrease in compression strength as moisture content increases is given by the equation below (Kellicutt, 1959: pg 80). It has been found that boxes made from many different types of board obey this equation.

$$wet\ CS = (dry\ CS) * (10)^{-3.01x} \ldots\ldots\ldots\ldots\ldots (1)$$

where: CS = compression strength of box, (lbs)

dry CS = compression strength at zero percent moisture content

x = board moisture content, (grams H_2O/100 grams dry board)

II. BOARD PROPERTIES

Box compression strength is related to various strength properties of the corrugated board from which it is made. Sheet density, or basis weight, for example is known to be correlated to box strength. The lower the sheet density, the lower the compression strength (Bristow and Kolseth, 1986: pg 307). Direct measurements of board strength are even more highly correlated to whole-box compression strength. Examples are flexural stiffness, ring crush resistance, edge crush resistance, flat crush resistance, pin-adhesion strength, puncture strength, and burst strength. The effect of each of these strength measurements on box strength will be discussed in detial.

Flexural stiffness

Flexural stiffness measures the bending strength of the combined board. A related property, bending stiffness, measures the bending strength of the components (Whitsitt, 1988: pg 163). Figure 1 illustrates the test procedure for measuring bending stiffness. Flexural stiffness of the combined board is dependent upon tensile stiffness of the components in the combined board. The higher the tensile stiffness, the greater the bending stiffness. For instance, kraft liner provides a higher tensile stiffness than a test liner. Kraft liner consists of 85% or more virgin kraft wood pulp while test linerboard satisfies the requirements of Rule 41 (The Dictionary of Paper, 1965: pg 267, 439). This leads to a higher box compression strength (Markstrom, 1988: pg 11).

Ring-Crush Test (RCT)

RCT is a measure of the compression resistance of the individual linerboard and medium materials used in the corrugated board. Figure 2 shows the test procedure for measuring ring crush strength. The RCT value has been used to gauge total package strength. However since the RCT value takes into account only the strength of the containerboard components, it cannot compensate for poor converting quality or insufficient package design (Santelli, 1991: pg 28).

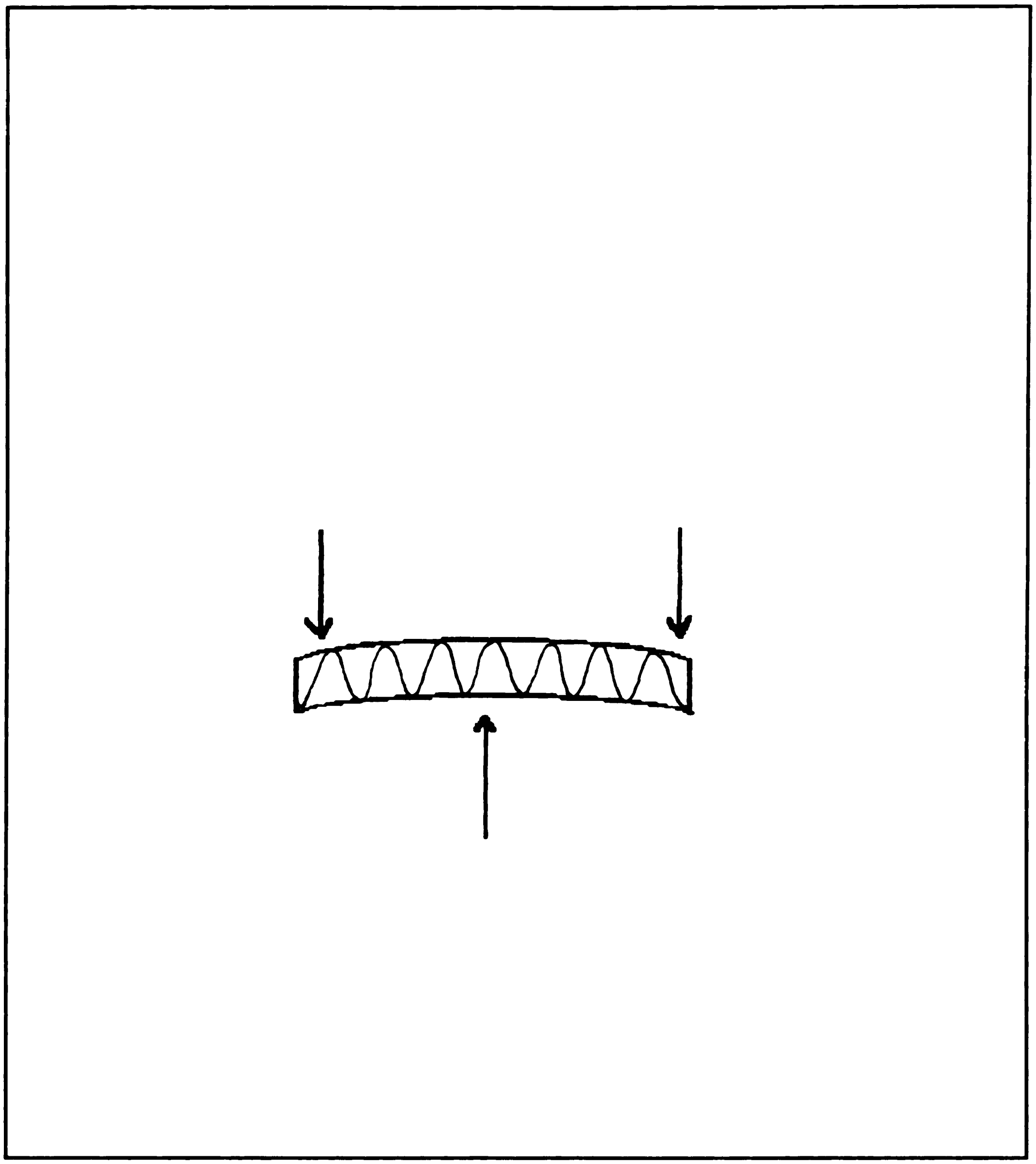

Figure 1: Bending Stiffness Measurement

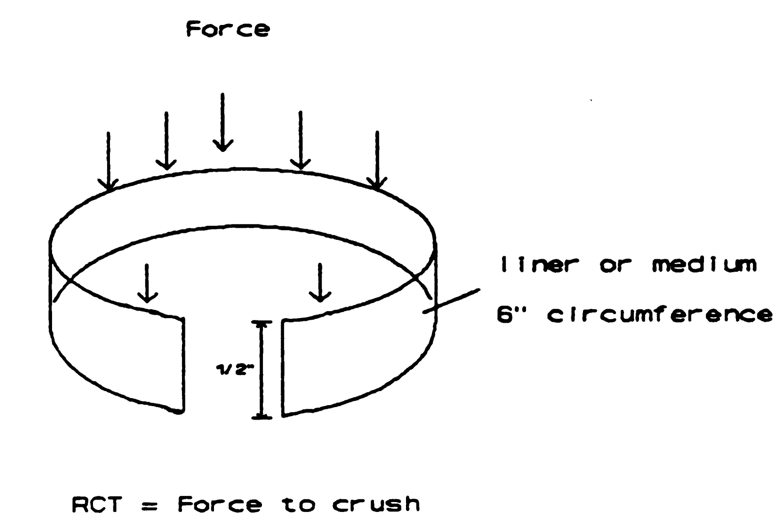

Figure 2: Ring Crush Test

Edgewise Crush Test (ECT)

The edge crush resistance of corrugated board is the strength property most widely used to predict whole box compression strength. Figure 3 shows the test set up for measuring edge crush resistance. There are two reasons for using the edgewise compression resistance of corrugated board to predict box strength. The first is that the edge crush strength measures the necessary force to collapse a short vertical sample of corrugated board and therefore simulates box compression. The second is that it appears in the McKee formula as follows (Santelli, 1991: pg 33, Kelsey, 1992: pg 18, Fibre Box Handbook Supplement, 1991: pg 70, and Thielert, 1986: pg 77).

$$CS = 5.87 * ECT * (ZH)^{1/2} \quad \text{..................(2)}$$

where: CS = top-to-bottom compression strength, (lbs)

ECT = edge crush resistance, (lbs/in)

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

h = board caliper, (thickness in inches)

The ECT has been used as an index for the estimating the stackability of boxes stored on pallets in warehouses. The higher the edgewise compression resistance, the better the stacking properties of the boxes (Thielert, 1986: pg 77). The ECT is related to both the stacking strength and the overall transportation performance of a corrugated board box

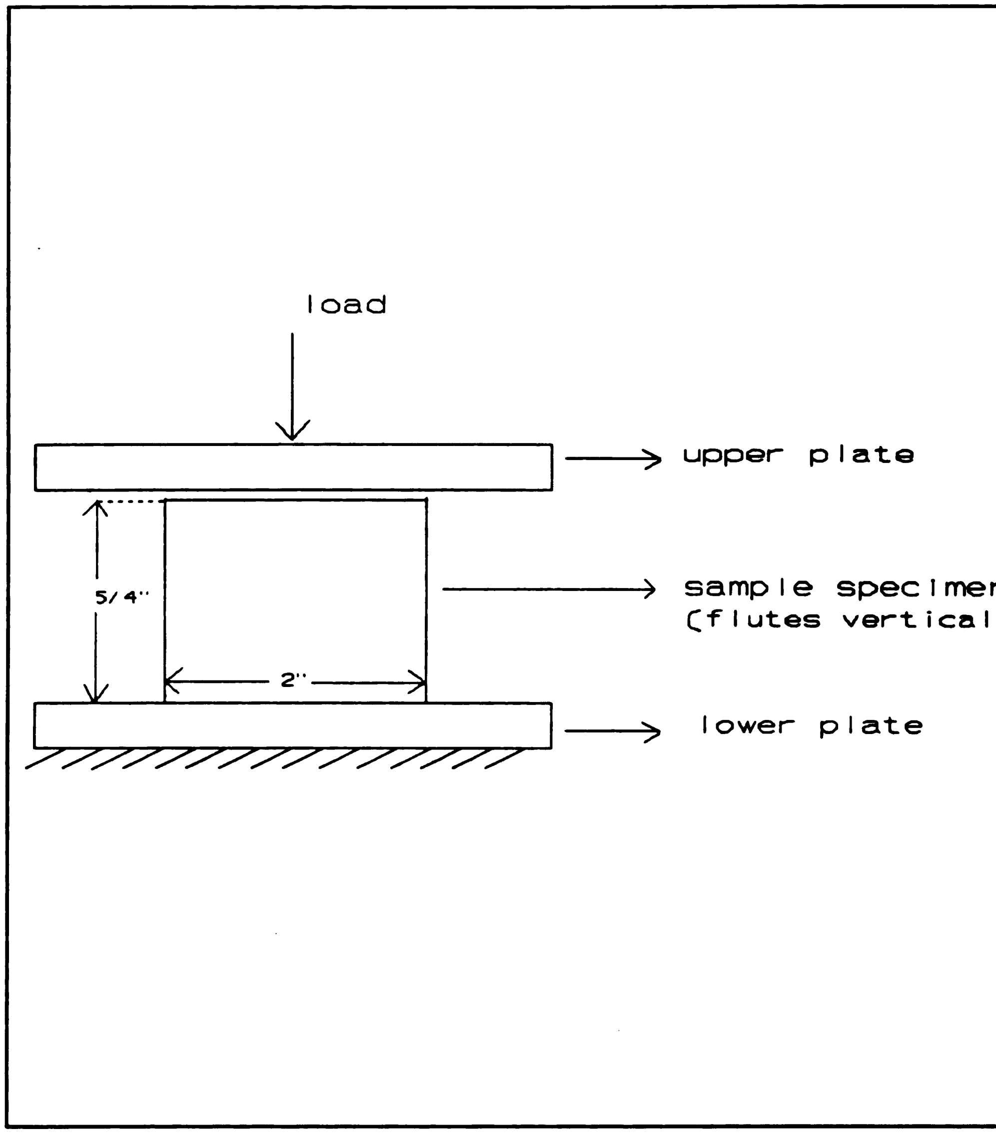

Figure 3: Edge Crush Test

(Markstrom, 1988: pg 17).

There are several ECT methods in use. Examples are ASTM D2808-69 and FEFCO method No.8. According to ASTM D2802-69 (Figures 3 and 4), the edges of the samples are first dipped in molten paraffin wax. The wax is used to reinforce the loaded edges of the specimens to prevent edge failure. For board grades with an ECT higher than 86 lb/in, paraffin wax impregnation alone cannot prevent edge failure however (Markstrom, 1988: pg 18 and Koning, 1986: pg 74). Other factors which affect the ECT are badly cut samples, a compression tester with non-parallel plates, and uncontrollable stress concentrations in the test piece. The compression speed also affects the ECT value. Edgewise compression resistance is usually higher when the compression speed is higher (Thielert, 1986: pg 78)

Another important factor that affects the ECT value is the manufacturing process. Combined boards made with more highly wet-pressed or densified liners and stronger mediums exhibit higher values for edgewise compression testing (Whitsitt, 1988: pg 163, 167). ECT can vary by as much as 40 percent due to poor corrugator practices that affect the quality of the liner and medium. Process controls such as adhesion, tension on the medium and liner webs, temperature, preconditioning, single face glue line width, and viscosity of the starch adhesive also greatly affect the ECT (Galvin, 1992: pg 22).

Since the medium carries most of the load in an edge

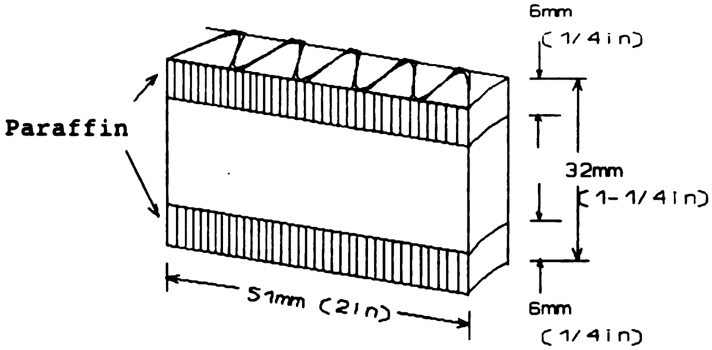

Figure 4: Waxed Specimens used for the edge crush test, according to ASTM D2808-69

crush test, properties of the medium such as recycled content and basisweight are expected to have the greatest influence on ECT and on whole box compression strength.

Flat Crush Test (FCT)

FCT is a measure of the ability of the corrugated board to resist being crushed under the action of a compressive force perpendicular to the board surface. Figure 5 shows the test procedure for measuring flat crush resistance. The flat crush resistance is a critically important property of corrugated board that is related to the strength of the corrugating medium (Daub, Hoke and Gottsching, 1990: pg 174). The stronger medium increases the flat crush strength and reduces crushing during conversion and product use (Maltenfort, 1988: pg 248 and Whitsitt, 1988: pg 167). About 30-40% of the flat crush potential is lost during fluting (Whitsitt and Sprague, 1987: pg 91).

Pin-adhesion

Pin adhesion is a test for the dry bond strength between the liner and medium as shown in Figure 6. This test is used in the manufacturing process as a quality control tool to monitor adhesive penetration and spotty adhesion (Daub, Hoke and Gottsching, 1990: pg 171 Maltenfort, 1988: pg 262 and TAPPI 821 om-87).

Bond failure can occur from cohesive failure, adhesive failure, or substrate failure. Cohesive failure is failure within the adhesive layer itself; adhesive failure appears at

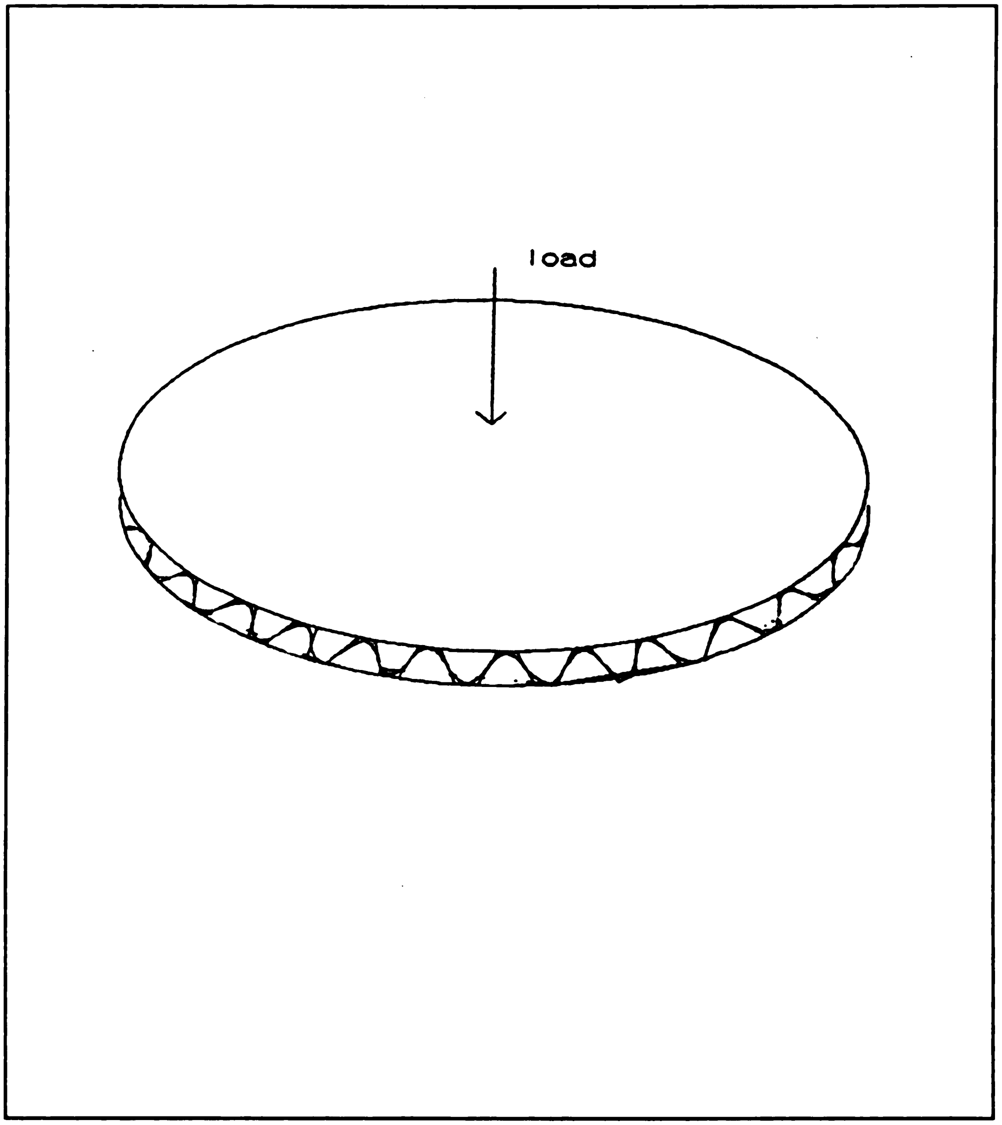

Figure 5: Flat Crush test Schematic

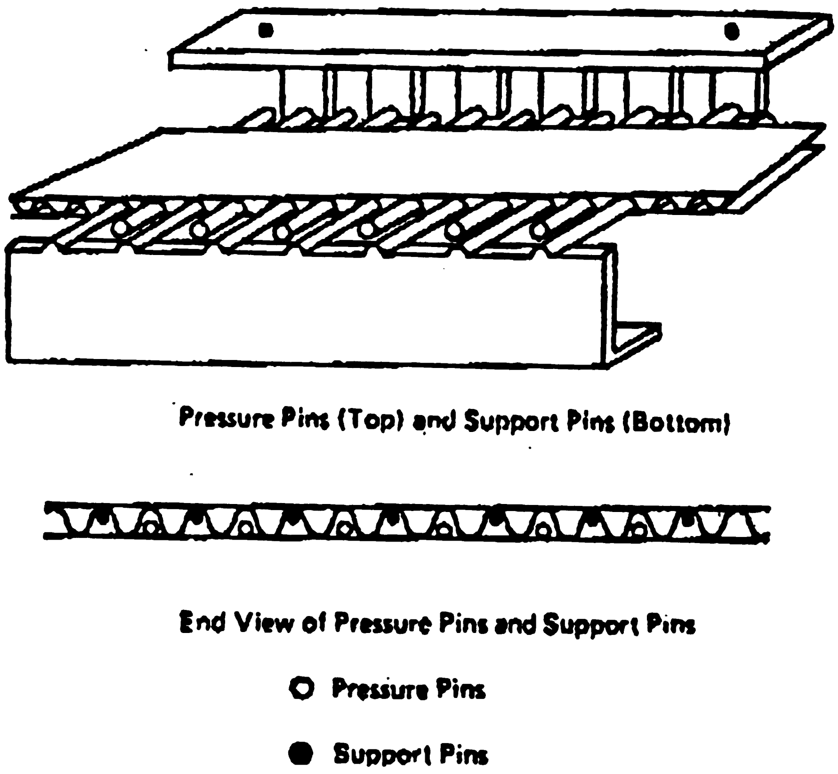

Figure 6: Pin-adhesion Test

the adhesive-substrate interface, and substrate failure happens within the paper itself (Shires, 1988: pg 67).

Low pin adhesion strength is correlated to a reduction in stacking performance particularly under long-term loads and high humidity conditions (Lorenz, 1990: pg 137). Low pin adhesion strength can occur in the manufacturing process as a result of the rapid drying of small amounts of glue before the corrugated medium comes into contact with the linerboard. An insufficient amount of glue to fill the cavities on the surface of rough papers can also cause low pin-adhesion strength (Daub, Hoke and Gottsching, 1990: pg 174). It has also been found that increased production speeds lead to decrease pin adhesion strength (Whitsitt and Baum, 1987: pg 111).

Puncture Test

According to TAPPI 803 OM-88, the puncture test is a measure the total energy required to crush the board before it can be punctured (Figure 7). Puncture strength is not as much dependent upon what the mill and the converter do but on the quality of the individual components, flute geometry, board design, and fabrication quality. The liner is the dominant factor in the puncture test of combined board in terms of improving stiffness.

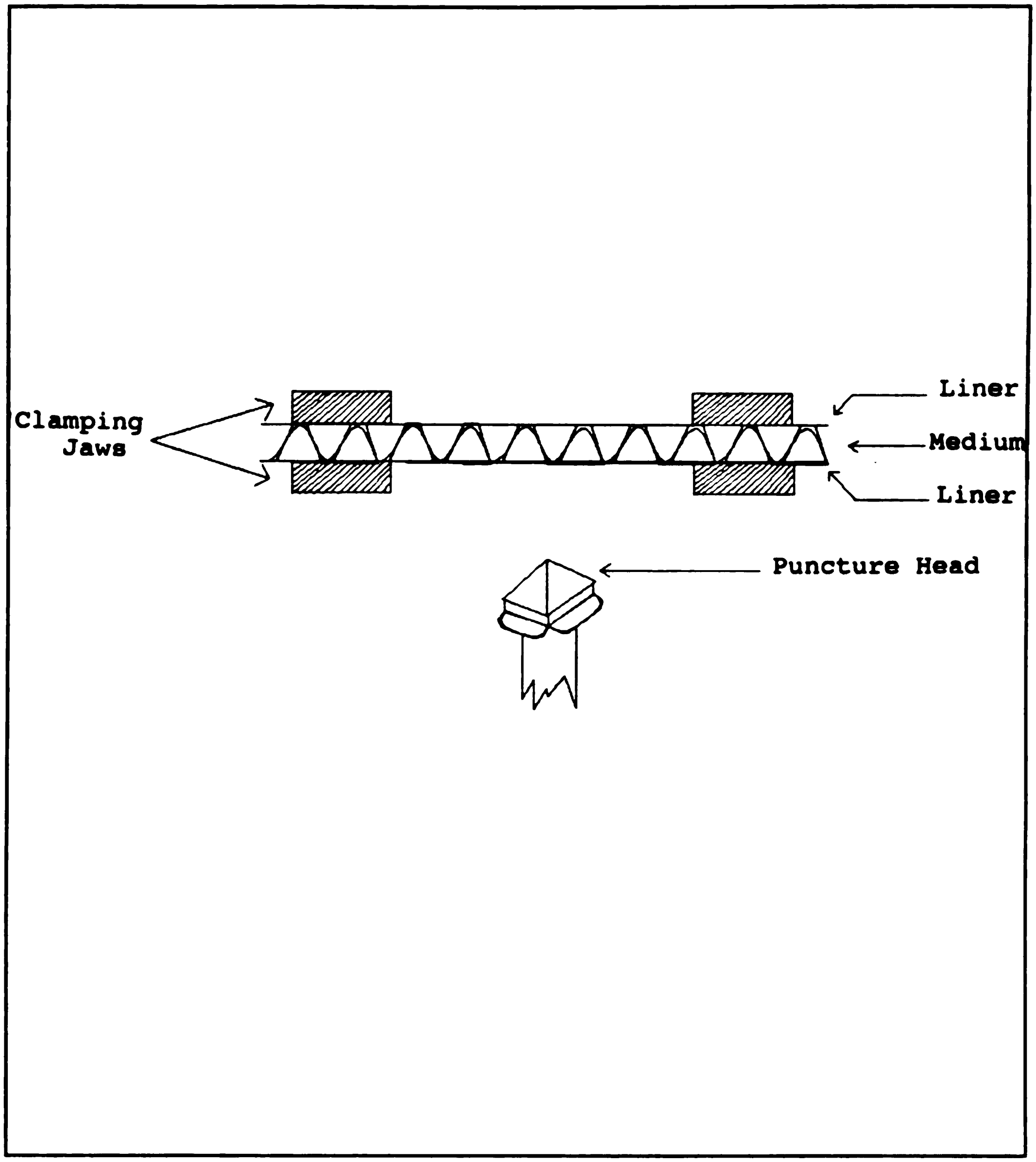

Figure 7: Schematic of Puncture Resistance according to TAPPI 803 om-88

Burst Test

In the burst test, a circular-shaped region of the corrugated board is stretched by a rubber membrane or diaphragm pushed by a piston until it bursts as shown in Figure 8 (Markstrom, 1988 : pg 42 and Kelsey, 1992: pg 17).

The bursting strength measures the containment capability of the board (Howes, 1990: pg 21) and therefore is influenced most by the strength of the liners. Burst strength does not however correlate directly with box compression strength (Markstrom, 1988: pg 42). In addition, the test results are sensitive to the way the specimen is tested. According to TAPPI 810 om-80, there is no standard requirement for the clamping pressure used to hold the specimen in place (Maltenfort, 1988: pg 245).

III. MANUFACTURING AND STRENGTH

Corrugated fiberboard may be made of singlewall, doublewall or triplewall corrugated fiberboard. In any case, the corrugated fiberboard is composed of two structural components, the corrugating medium and the linerboard, which must be then combined in a high-speed fluting, gluing, and drying process.

The corrugating medium is paperboard is shaped to form the fluted or corrugated center of the board. Manufacturers have discovered that the strength of the medium is very important to the overall strength of the board (Kelsey, 1992:

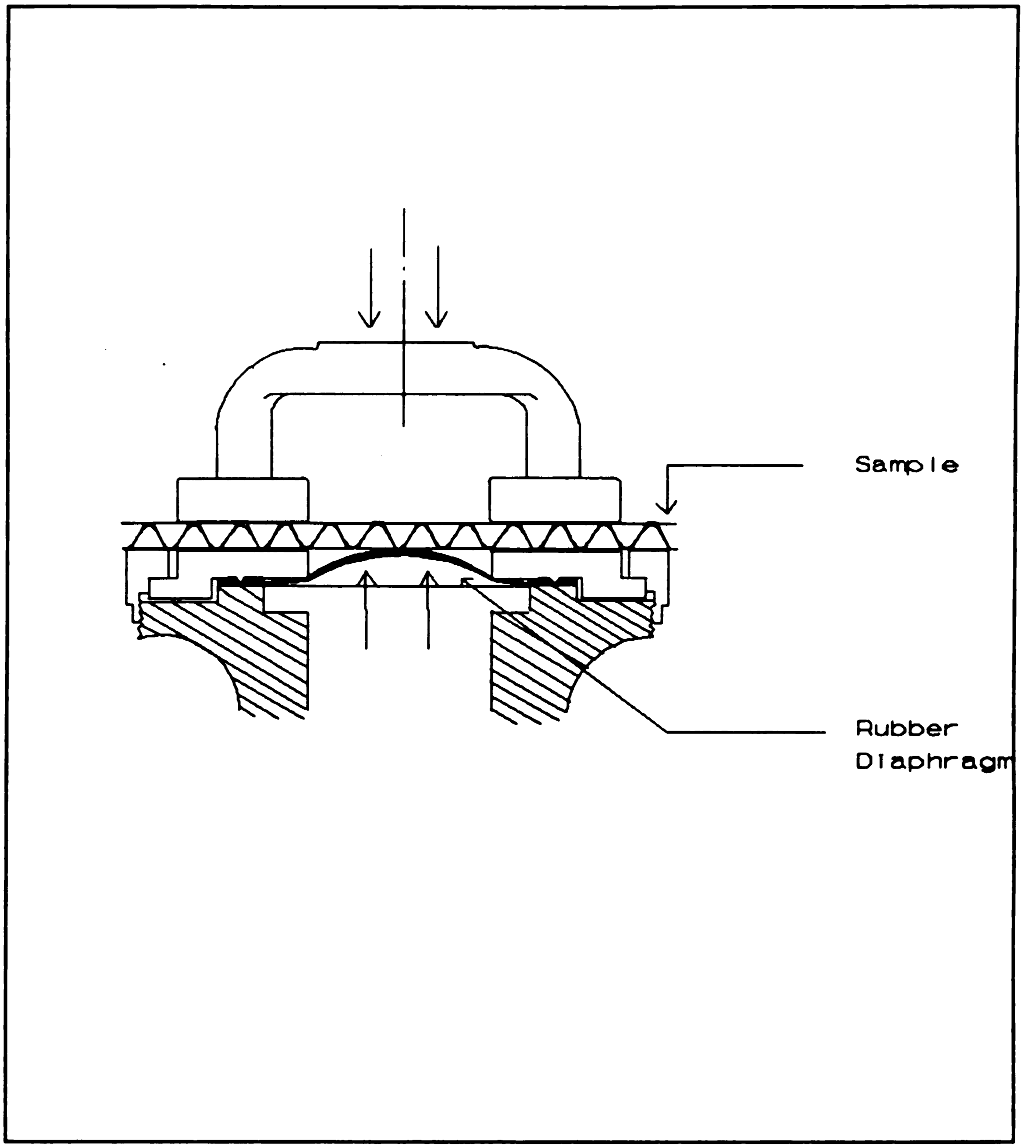

Figure 8: Schematic of the Mullen test according to TAPPI 810 om-80

pg 16-19). Performance results such as flat crush strength and edgewise compressive strength are strongly dependent on the strength of the medium.

The compressive strength of the medium can be significantly reduced by the fluting process. During fluting, the corrugating medium is exposed to high tensile, bending, and compressive stresses in order to form the fiber-to-fiber bond between the fluting and the linerboard. These stresses can cause lower combined board compressive and flat crush strengths (Whitsitt and Sprague, 1987: pg 91 and Bever, 1986: pg 928).

During the combined board process, the corrugating medium must contact the glue as shown in Figure 9. Minimizing contact stresses during the fluting and combining processes enhances edgewise crush and flat crush strength in the combined board (Whitsitt and Baum, 1987: pg 110).

Recycling lowers strength properties such as edge crush flat cush, burst, tear, fold, ring crush, tensile strength, etc. because the fibrils on the surface of the fibers collapse somewhat upon drying and rewetting and lower the strength of the hydrogen bond between the fibers (Bever, 1986: pg 4125, and Koning and Godshall, 1975: pg 40). Cleaning also affects strength. The cleaner the recycled board, the greater the decrease in the strength properties. For example, postconsumer waste pulp with lighter cleaning has proved to be stronger than more heavily cleaned plup due to the process employed in cleaning the pulp. Losses have tended to increase as the

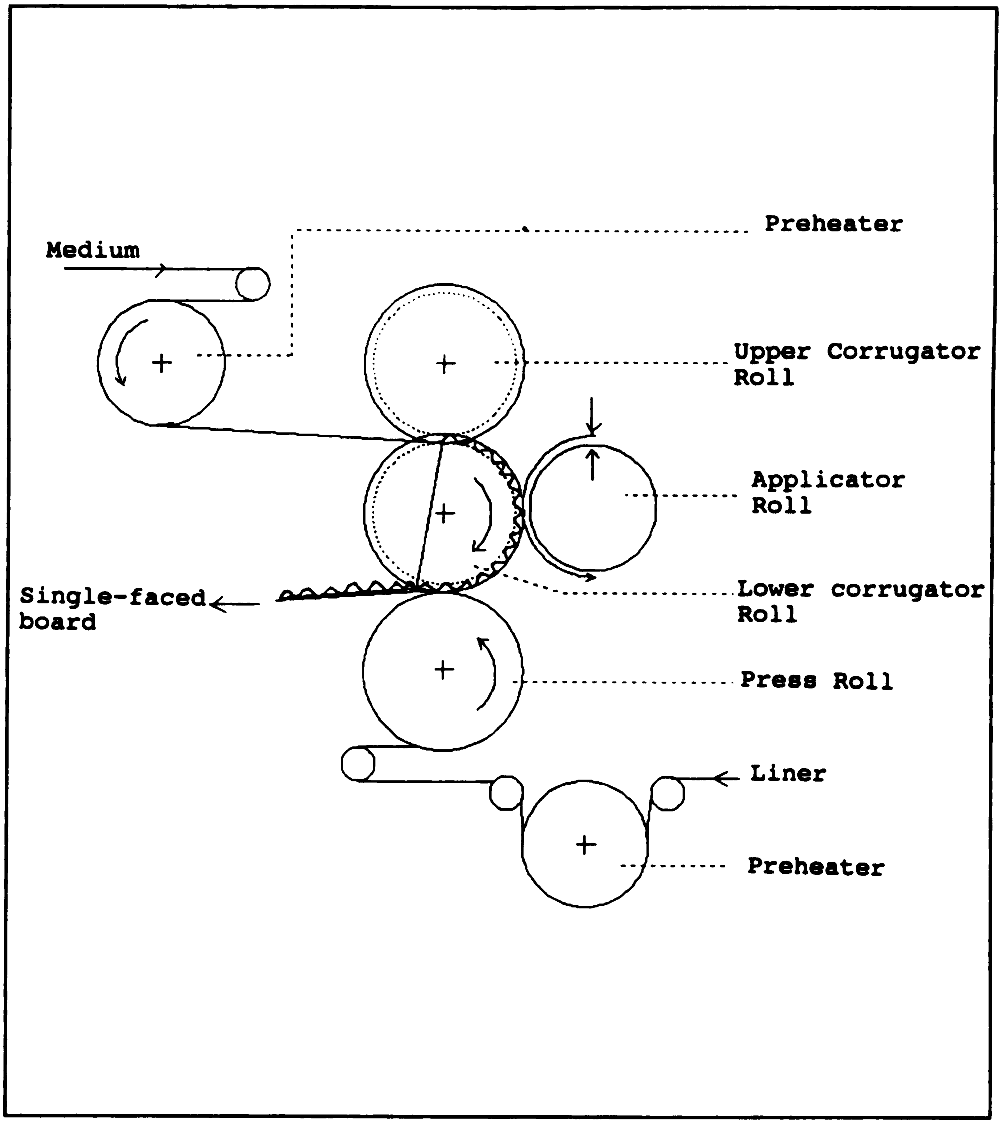

Figure 9: Combined Board Process

percentage of the recycled fiber increases (Fahey and Bormett, 1982: pg 110). Therefore, it is believed by some boxmakers that the best quality corrugated fiberboard is recycled material made of only Old Corrugated Containers (OCC) when the ratio of virgin kraft to recycled materials is 80:20 (Huck, 1991: pg 23). Most corrugated fiberboard mills produce 100% recycled medium with 100% Old Corrugated Containers (OCC) (Huck, 1991: pg 23). The corrugated industry has been using a certain amount of OCC and Double-lined kraft (DLK) cuttings in the manufacture of linerboard for years. Virgin kraft now consists of linerboard with 80% virgin fiber and 20% recycled fiber (Huck, 1991: pg 23-24).

Because of the shorter fibers, recycled fiber leads to converting problems in the corrugator and manufacturing problems on the paper machine. Since the recycled medium tends to fracture, the corrugating speed and web tension has to be reduced to complete runs. It has been found that the refined material showes a greater tendency to crack than the unrefined (Koning and Godshall, 1975: pg 38, 146-147 and Kroeschell, 1992: pg 35). The medium has become more susceptible to cracking on the corrugator when recycled fiber is repeatedly used. Because repeatedly recycled fibers continue to be shortened as they are refined, this has also caused a decrease the drainage rate on the paper machine and a reduction in the production rate due to lower speeds. The greatest loss in strength properties occur between the virgin material and the first recycling, rather than between subsequent recyclings

(Koning and Godshall, 1975: pg 40 and Kroeschell, 1992: pg 34).

Corrugated manufacturers today are expected to make 100% recycled linerboard even if they believe that the recycled content should not exceed 20% in high performance liners (Kelsey, 1992: pg 18 and Kishbaugh, 1990: pg 28). Since cylinder linerboard differs in physical properties from Fourdrinier linerboard, an evaluation of the effects of recycling on the strength properties might be different (Koning and Godshall, 1975: pg 38).

To overcome the reduction in strength properties of recycled linerboard and corrugated containers, the recycling fiber should be more refined. But this leads to a decrease in the production rate and this is a more serious problem for recycled fiber use (Koning and Godshall, 1975: pg 37, 40).

In the United States, OCC has been added to kraft liners in higher proportions to improve the strength properties of the linerboard (Uutela and Black, 1990: pg 51). It has been found that the addition of recycled OCC to the furnish improves impact resistance of the container (Horn, Bormett and Setterholm, 1988: pg 146).

When recycled paper is used, delamination is a common problem. This is because recycled paper is less porous so that adhesive penetration becomes a problem. To solve the problem of delamination, better adhesive formulations must be used by the corrugating industry: a lower viscosity adhesive provides a thin texture and penetrates or interacts with the paper faster than a viscous or thick texture material, for example (Wallace, Young and Fitt, 1991: pg 26-27).

EXPERIMENTAL PROCEDURES

TEST MATERIALS

The fiberboard materials used in this study were supplied by seven commercial manufacturers of recycled corrugated board. The range of properties of the boards used were as described below:

<u>Board Specifications</u>

Corrugation: C-flute, Single-wall

Basis weight of linerboard: 35-100 lb/1000 ft^2

Basis weight of corrugating medium: 26 and 33 lb/1000 ft^2

Quoted Burst Strength: 173 to 275 psi

Caliper: 5/32 inches

Recycled content of liner board: 0-100 %

Recycled content of medium: 0-100%

Type of recycled content: Old corrugated container(OCC)
Double line Kraft (DLK)
Post-consumer waste

Sheet size: 58"X24" (flute direction perpendicular to the length) th

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There were 15 types of corrugated fiberboard supplied by the seven commercial manufacturers. The details are given in Table 1. No "control" board with zero percent recycled content could be used because none is presently manufactured. All corrugated board presently referred to as "virgin kraft" contains at least 20% recycled content (Huck, 1991: pg 23-24). The basisweights, recycled contents, and burst strengths referred to in Table 1 are all values quoted by the manufacturer. The accuracy and variability of these number is not known. Also, the type of recycled content (OCC, DLK, etc) is not known for all of them.

APPARATUS

The following equipment was used to conduct the performance tests on the recycled board

1. Environmental Chamber

   Brand: Nor-Lake Scientific no.3 and Chrysler Koppin refrigerator

2. Coolers: Used to protect conditioned samples during transfer from chambers to test equipment.

   Brand: Coleman

3. Thermo-hygrometer

   Brand: Cole-Parmer, model 3309-60

4. Sample Making Machine

   Brand: S&S Coorugated Paper Machine

Table 1: Manufacturer, burst strength, basis weight of linerboard/medium, and % recycled content of 15 board types

board no.	manufac -turer	Quoted Burst Strength (psi)	Basis weight ($lb/1000ft^2$) li/me/li	recycled content (%)	
				li	me
1	A	200	42/26/42	20	100
2	B	*	35/26/35	0	35
3	B	*	42/26/42	10	35
4	C	*	42/26/42	44	70.5
5	C	*	42/33/42	44	70.5
6	D	173	35/26/35	27	33
7	D	195	42/33/42	37	33
8	D	186	42/26/42	5	33
9	D	187	42/26/42	37	35
10	E	200	100/26/100	100	0
11	F	*	42/26/42	100	100
12	G	175	42/26/33	32	100
13	G	200	42/26/42	30	100
14	G	275	69/26/69	21	100
15	G	250	55.5/26/55.5	25	100

Note: * - unavailable
li - Linerboard
me - Medium

Maufacturers; A = Viking Paper Corporation
B = J&J Southeast
C = Willamette Industries, Inc.
D = Weyerhaeuser
E = 4-M Corporation
F = Stone Container Corporation
G = Corru-Kraft Co.

5. Sample Cutter for Edge Crush Test

   Brand: TMI

   Size: 2"X 1.25"

6. Circular Sample Cutter for Flat Crush

   Brand: TMI

   Radius size: 1.784"

7. Crush Tester Model no. 17-36

   Brand: TMI

8. Oven for Moisture Content Test

   Brand: Precision Scientific P/S Model 524

9. Mass Balance

   Brand: Mettler AE 160

10. Beach Puncture Tester

    Brand: TMI

11. Mullen Tester

    Brand: Perkins Holyoke

12. Compression Tester

    Brand: Lansmont

SAMPLE PREPARATION

The board samples supplied by the manufacturers were used to make test specimens for the various board tests (edge crush, flat crush, etc.) and for the whole-box compression strength test. For boards 10, 11, and 14 in Table 1, the samples supplied were either already scored by the manufacturer or not large enough so that the chosen test box for compression (a

16"X12"X10" RSC) could not be made. Prior to testing, test specimens for various boards were conditioned in one of three environments; the TAPPI standard condition, a refrigated storage condition, and a tropical condition. In this way, the effect of moisture content on strength could also determined. The boxes were conditioned only at TAPPI standard conditions. The number and size of the samples were as follows:

1. Five board specimens per humidity condition measuring 12 inches wide and 12 inches long for each type of board for bursting strength testing.
2. Eight board specimens per humidity condition measuring 10 inches wide and 10 inches long for each type of board for puncture strength testing.
3. Ten board specimens per humidity condition measuring 3 inches wide and 4 inches long for each type of board for moisture content determination.
4. Two strips, 2 inches wide and 12 inches long, per humidity condition for each board type for edge crush testing. The flutes were parallel to the long axis of the strips. Each strip was then cut into 5 specimens 1.25 inches wide and 2 inches long with the TMI sample cutter. Ten specimens were made for each board type. The edges of the cut specimens were dipped into wax according to ASTM D 2808-69.
5. Ten circular specimens of each board type for each humidity condition for flat crush testing.
6. Ten specimens per humidity condition of each board

type measuring 2 inches wide and 6 inches long, with the flutes running parallel to the width for pin-adhesion testing.

7. Ten RSC style boxes measuring 16"X 12" X 10" for each board type for compression testing. The blank for the box is shown in Figure 10. The size of box was chosen because it represents the average size used in the grocery industry.

CONDITIONING

The 63 specimens per board type and the two coolers were conditioned for 5 days as follows before testing:

1. TAPPI standard condition: 73.4±2°F and 50±2 %RH
2. Refrigerated storage: 41.0±4°F and 85±5 %RH
3. Tropical conditions: 104±4°F and 85±5 %RH

The temperatures and humidities for the refrigerated and tropical conditions are consistent with the recommendations of ASTM D4332-89. All boxes were conditioned only at TAPPI standard conditions.

TEST METHODS

Edge Crush Testing

The edge crush values for the conditioned board specimens were determined using the test procedure outlined in ASTM D2808-69. Ten specimens or replications of each board

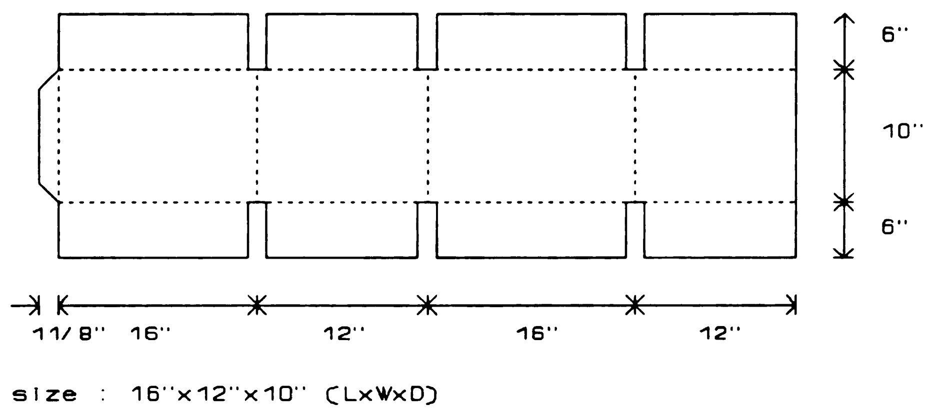

Figure 10: Box blank for the compression tests

type were used for each condition. There were 3 conditions and 15 board types so that the total number of tests for edge crush testing was 10 replications X 3 conditions X 15 board types = 450 tests.

Flat Crush Testing

The flat crush values for the conditioned board specimens were determined using the test procedure outlined in TAPPI 808 om-86. Ten specimens or replications of each board type were used for each condition. There were 3 conditions and 15 board types so that the total number of tests for flat crush testing was 10 replications X 3 conditions X 15 board types = 450 tests.

Moisture Content Determination

The moisture content values for the conditioned board specimens were determined using the test procedure outlined in ASTM D644-55. Ten specimens or replications of each board type were used for each condition. There were 3 conditions and 15 board types so that the total number of tests for moisture content determination was 10 replications X 3 conditions X 15 board types = 450 tests.

Pin-adhesion Testing

The pin-adhesion strength values for the conditioned board specimens were determined using the test procedure outlined in TAPPI 821 om-87. Ten specimens or replications of each board type were used for each condition. There were 3 conditions and 15 board types so that the total number of tests for pin-adhesion testing was 10 replications X 3 conditions X 15 board types = 450 tests.

Puncture Testing

The puncture values for the conditioned board specimens were determined using the test procedure outlined in TAPPI 803 om-88. Eight specimens or replications of each board were used for each condition. There were 3 conditions and 15 board types so that the total number of tests for puncture testing was 8 replications X 3 conditions X 15 board types = 360 tests.

Bursting Strength Testing

The bursting strength values for the conditioned board specimens were determined using the test procedure outlined in TAPPI 810 om-80. There were four readings taken on each of the 5 specimens for total of 20 replications for each condition. There were 3 conditions and 15 board types so that the total number of tests for burst strength was 20 replications X 3 conditions X 15 board types = 900 tests.

Compression Testing

The compression strengths of the conditioned boxes were determined in accordance with ASTM D642-76. Ten boxes of each board typed were used. Since, for board No.10, 11, and 14, the samples were either already scored for a particular box size or not large enough so that boxes for the compression test could be made. Therefore there were 12 board types, and the total number of tests was 10 boxes X 12 board types = 120 tests. No compression strength testing was done at the refrigerated and tropical conditions because there was not enough material available from the supplier to do these tests.

Flexural Stiffness

Flexural stiffness was not tested because of the limited amount of material available.

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RESULTS AND DISCUSSION

The results of the various board and box performance tests are shown in Tables 2-16. Each table gives the results for a particular board. The combined board basis weight is taken to be the sum of the individual liner and medium basis weights in order to easily make comparisons between different boards. In Tables 2-16, li = liner and me = medium.

I. BOX COMPRESSION STRENGTH VERSUS COMBINED BOARD RECYCLED CONTENT

The compression strengths of the 16"X12"X10" boxes made from each of the 12 board types (Tables 2-10, 13-14 and 16) were plotted against the recycled content of the medium in Figure 11. The recycled content of the medium alone was chosen because it is primarily the medium which determines strength in this test. The three numbers beside the data points in Figure 11 represent the board number, the combined board basis weight, and twice the standard deviation on compression strength (for 95% confidence limits) respectively for that particular board. The results show that there is no definite trend between box compression strength and medium

Tab

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Table 2: Board No.1.
Manufactured by Viking Paper Corporation.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 20/100/20 = li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation.

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	6.7/0.2	14.1/0.3	10.7/0.1
Edge crush (lb/in)	40.8/2.0	24.0/1.5	34.7/3.1
Flat crush (lb/in^2)	22.8/2.7	13.9/3.2	15.2/0.9
Pin-adhesion (lb/in)	58.6/4.2	41.0/4.1	40.8/6.0
Puncture resistance (lb-in)	74.4/2.7	71.8/2.7	70.0/2.7
Bursting strength (psi)	205/49.8	220/37.6	230/45.8
Box compression strength (lb) 16"x12"x10" RSC	667/39.9	-	-

Tab

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Be st l

Table 3: Board No.2.
Manufactured by J&J Southeast.
Basis weight (lb/1000 ft^2) = 35/26/35 = li/me/li.
Recycled content (%) = 0/35/0 = li/me/li.
Combined board basis weight= 96 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.1/0.1	14.1/0.1	10.7/0.1
Edge crush (lb/in)	28.8/2.0	23.5/2.2	28.4/2.2
Flat crush (lb/in^2)	19.8/1.1	13.2/3.0	16.5/1.6
Pin-adhesion (lb/in)	45.7/6.3	47.6/2.5	45.5/2.5
Puncture resistance (lb-in)	61.2/1.8	63.8/1.8	60.3/1.8
Bursting strength (psi)	170/37.6	230/29.2	185/31.8
Box compression strength (lb) 16"x12"x10"RSC	727/84.3	-	-

Table 4: Board No.3.
Manufactured by J&J Southeast.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 10/35/10 = li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.0/0.1	14.1/0.3	10.9/0.1
Edge crush (lb/in)	23.0/2.2	21.8/2.3	22.5/4.2
Flat crush (lb/in^2)	23.0/3.5	14.7/3.6	21.2/6.0
Pin-adhesion (lb/in)	56.9/3.5	44.4/1.1	47.4/1.5
Puncture resistance (lb-in)	66.5/1.8	70.9/1.8	67.4/1.8
Bursting strength (psi)	300/39.4	300/23.6	275/25.9
Box compression strength (lb) 16"x12"x10"RSC	675/99.6	-	-

Table 5

Prope
Moist (gra 100 boa
Edge (lb
Flat (lb
Pin- (lb
Punc resi (lk
Burs (ps
Box str 16"

Table 5: Board No.4.
Manufactured by Willamette Industries, Inc.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 44/71/44= li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	6.7/0.1	15.1/0.2	10.8/0.1
Edge crush (lb/in)	34.2/3.0	21.6/1.5	26.0/2.0
Flat crush (lb/in^2)	25.3/1.0	12.0/1.0	18.6/1.1
Pin-adhesion (lb/in)	52.0/5.9	51.7/6.1	53.1/2.4
Puncture resistance (lb-in)	62.9/1.8	64.7/1.8	59.4/1.8
Bursting strength (psi)	180/40.6	190/17.0	210/29.0
Box compression strength (lb) 16"x12"x10"RSC	700/78.7	-	-

Table

Prop
Mois (gra 100 boa
Edge (lb
Flat (lb
Pin- (lb
Punc resi (lb
Burs (ps
Box stre 16"x

Table 6: Board No.5.
Manufactured by Willamette Industries, Inc.
Basis weight (lb/1000 ft^2) = 42/33/42 = li/me/li.
Recycled content (%) = 44/71/44= li/me/li.
Combined board basis weight= 117 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	6.7/0.1	14.1/0.2	10.4/0.1
Edge crush (lb/in)	36.7/3.2	26.3/2.2	33.4/5.2
Flat crush (lb/in^2)	28.4/1.3	14.4/0.6	22.6/0.7
Pin-adhesion (lb/in)	46.7/5.8	46.3/2.0	48.0/4.4
Puncture resistance (lb-in)	70.0/0.9	74.4/1.8	70.0/0.9
Bursting strength (psi)	165/9.7	220/24.8	185/27.8
Box compression strength (lb) 16"x12"x10"RSC	770/111.4	-	-

Table 7: Board No.6.
Manufactured by Weyerhaeuser.
Basis weight (lb/1000 ft^2) = 35/26/35 = li/me/li.
Recycled content (%) = 27/33/27 = li/me/li.
Combined board basis weight= 96 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	6.8/0.2	15.8/0.2	10.5/0.2
Edge crush (lb/in)	39.0/4.0	19.1/1.0	27.4/1.8
Flat crush (lb/in^2)	24.4/3.1	18.3/1.0	18.8/1.6
Pin-adhesion (lb/in)	42.4/6.4	42.1/2.4	47.8/5.0
Puncture resistance (lb-in)	61.2/2.7	64.7/2.7	62.0/1.8
Bursting strength (psi)	145/13.4	195/23.1	135/14.2
Box compression strength (lb) 16"x12"x10"RSC	586/70.4	-	-

Table 8: Board No.7.
Manufactured by Weyerhaeuser.
Basis weight (lb/1000 ft^2) = 42/33/42 = li/me/li.
Recycled content (%) = 37/33/37 = li/me/li.
Combined board basis weight= 117 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.1/0.2	15.4/0.2	10.6/0.2
Edge crush (lb/in)	37.0/2.2	21.1/1.0	32.5/3.6
Flat crush (lb/in^2)	34.0/1.1	12.5/1.5	28.2/0.7
Pin-adhesion (lb/in)	48.1/2.2	35.4/2.4	43.3/4.6
Puncture resistance (lb-in)	66.5/3.5	74.4/1.8	69.1/1.8
Bursting strength (psi)	150/13.5	205/18.9	165/26.6
Box compression strength (lb) 16"x12"x10"RSC	713/90.9	-	-

Table

Prop
Mois (gra 100 boa
Edge (lb
Flat (lb
Pin- (lb
Punc res (lb
Burs (p
Box str 16"

Table 9: Board No.8.
Manufactured by Weyerhaeuser.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 5/33/5 = li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.3/0.1	14.8/0.2	10.9/0.5
Edge crush (lb/in)	40.0/5.1	23.9/2.6	33.6/0.8
Flat crush (lb/in^2)	25.5/2.2	13.5/1.3	18.4/1.3
Pin-adhesion (lb/in)	51.6/8.2	35.2/4.5	44.2/3.4
Puncture resistance (lb-in)	69.1/2.7	72.7/2.7	69.1/3.5
Bursting strength (psi)	170/32.7	220/29.3	180/33.9
Box compression strength (lb) 16"x12"x10"RSC	806/83.0	-	-

Table 10: Board No.9.
Manufactured by Weyerhaeuser.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 37/35/37 = li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.1/0.1	16.4/0.3	10.6/0.1
Edge crush (lb/in)	34.3/3.9	19.7/1.3	27.5/2.8
Flat crush (lb/in^2)	19.5/1.2	10.3/1.0	16.4/5.6
Pin-adhesion (lb/in)	36.1/9.6	31.8/1.2	41.6/2.5
Puncture resistance (lb-in)	60.3/3.5	66.5/0.9	61.2/2.7
Bursting strength (psi)	175/28.0	225/15.0	140/29.3
Box compression strength (lb0 16"x12"x10"RSC	598/179.2	-	-

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Table 11: Board No.10.
Manufactured by 4-M Corporation.
Basis weight (lb/1000 ft^2) = 100/26/100 =li/me/li.
Recycled content (%) = 100/0/100 =li/me/li.
Combined board basis weight= 226 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.6/0.1	15.7/0.4	10.7/0.1
Edge crush (lb/in)	37.6/5.9	21.2/2.1	28.3/4.3
Flat crush (lb/in^2)	21.5/1.6	11.4/1.6	15.5/0.7
Pin-adhesion (lb/in)	40.0/1.5	36.4/3.1	32.9/4.2
Puncture resistance (lb-in)	58.5/2.7	56.7/1.8	56.7/2.7
Bursting strength (psi)	145/17.4	200/17.1	155/19.1
Box compression strength (lb) 16"x12"x10"RSC	-	-	-

Table 12: Board No.11.
Manufactured by Stone Container Corporation.
Basis weight (lb/1000 ft^2) = 42/26/42 =li/me/li.
Recycled content (%) = 100/100/100=li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.4/0.1	14.6/0.3	11.1/0.1
Edge crush (lb/in)	37.6/5.8	22.3/1.9	33.9/1.8
Flat crush (lb/in^2)	21.5/1.0	13.2/0.9	19.5/1.9
Pin-adhesion (lb/in)	47.2/4.7	44.8/1.9	55.2/4.1
Puncture resistance (lb-in)	68.2/0.9	68.2/1.8	68.2/1.8
Bursting strength (psi)	180/15.4	215/34.5	210/24.8
Box compression strength (lb) 16"x12"x10"RSC	-	-	-

Table 13: Board No.12.
Manufactured by Corru-Kraft.
Basis weight (lb/1000 ft^2) = 42/26/33 =li/me/li.
Recycled content (%) = 32/100/32 =li/me/li.
Combined board basis weight= 101 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.8/0.1	15.2/0.2	10.7/0.2
Edge crush (lb/in)	32.6/2.4	17.4/1.3	29.0/2.0
Flat crush (lb/in^2)	18.3/3.4	10.1/0.3	13.7/4.7
Pin-adhesion (lb/in)	50.0/2.9	40.7/2.7	46.7/3.0
Puncture resistance (lb-in)	62.9/1.8	64.7/1.8	61.2/1.8
Bursting strength (psi)	175/30.3	220/40.6	185/47.5
Box compression strength (lb) 16"x12"x10"RSC	643/61.1	-	-

Table

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Fla (l
Pin (l
Pun res (l
Bur (p
Box str 16

Table 14: Board No.13.
Manufactured by Corru-Kraft.
Basis weight (lb/1000 ft^2) = 42/26/42 = li/me/li.
Recycled content (%) = 30/100/30= li/me/li.
Combined board basis weight= 110 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.5/0.3	16.6/0.2	11.9/0.1
Edge crush (lb/in)	35.5/2.6	18.8/1.3	28.8/1.7
Flat crush (lb/in^2)	17.8/0.8	9.2/0.8	13.7/0.6
Pin-adhesion (lb/in)	45.9/4.2	38.6/2.2	40.2/3.6
Puncture resistance (lb-in)	66.5/0.9	65.6/0.9	63.8/1.8
Bursting strength (psi)	255/32.3	275/25.6	265/17.9
Box compression strength (lb) 16"x12"x10"RSC	695/56.7	-	-

Table

Propo
Mois (gra 100 boa
Edge (lb
Flat (lb
Pin- (lb
Punc res (ll
Burs (p
Box str 16"

Table 15: Board No.14.
Manufactured by Corru-Kraft.
Basis weight (lb/1000 ft^2) = 69/26/69 = li/me/li.
Recycled content (%) = 21/100/21= li/me/li.
Combined board basis weight= 164 lb/1000 ft^2
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Moisture content (grams water per 100 grams dry board)	7.3/0.3	15.3/1.0	10.4/0.2
Edge crush (lb/in)	57.0/7.4	29.9/1.6	49.2/3.4
Flat crush (lb/in^2)	19.4/2.1	10.4/0.6	15.1/0.6
Pin-adhesion (lb/in)	56.0/3.1	42.5/1.8	47.6/2.4
Puncture resistance (lb-in)	96.6/1.8	119.6/1.8	94.8/4.4
Bursting strength (psi)	310/44.7	355/23.1	305/27.2
Box compression strength (lb) 16"x12"x10"RSC	-	-	-

Table 16: Board No.15.
Manufactured by Corru-Kraft.
Basis weight ($lb/1000\ ft^2$ = 55.5/26/55.5=li/me/li.
Recycled content (%) = 25/100/25 =li/me/li.
Combined board basis weight= 136 $lb/1000\ ft^2$
Values listed are mean/standard deviation:

Properties	Tappi Std.Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
Edge crush (lb/in)	47.9/2.1	23.8/2.8	38.5/4.6
Flat crush (lb/in^2)	16.6/1.6	8.5/0.3	13.4/0.5
Pin-adhesion (lb/in)	50.0/1.7	33.9/6.7	41.3/1.9
Puncture resistance (Joule)	8.2/0.4	8.3/0.2	8.0/0.2
Bursting strength (psi)	270/36.3	360/24.9	300/42.6
Box compression strength 16"x12"x10" (lb)	770/106.3	-	-

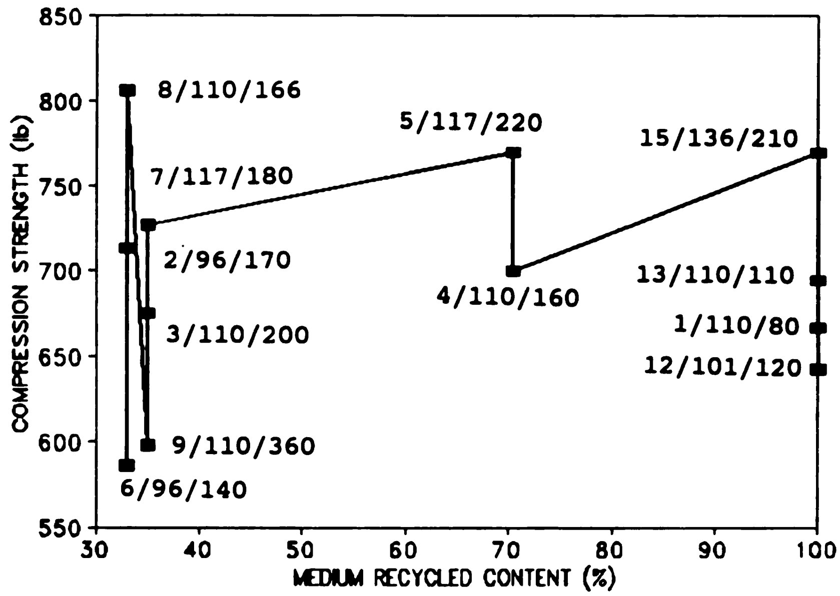

Figure 11: Box compression strength versus medium recycled content at TAPPI standard conditions

recycled content. It was expected that the compression strength would decrease as recycled content increased. The reason for the lack of any definite trend may be due to the fact that the combined board basis weights (CBBW) in Figure 11 are all different. In Figure 12, only the six boards with a CBBW of 110 lb/1000ft^2 are plotted against medium recycled content. It can be seen that there is still no definite trend between box compression strength and medium recycled content as would be expected. In other words, for a given combined board basis weight, the compression strength does not continue to decrease as recycled content increases. However, since the variation in compression strength for all boards is quite high, it may still be possible that the compression strength does in fact decrease steadily as medium recycled content increases. The approximate 95% confidence limits for board number 9 for example are 600-360 = 240 lbs and 600+360 = 960 lbs. The true compression strength for board number 9 could therefore be higher than the data points that follow it (boards number 4, 13, and 1). This is also true of board number 3 which has the next highest variation compared to all other boards. In other words, the data points corresponding to board number 3 and 9 could lie below that for board number 8 and above those for the remaining boards, which would then produce the expected trend. There is simply too much variation in compression strength to make this conclusion with any certainty.

There are two other factors which could account for the

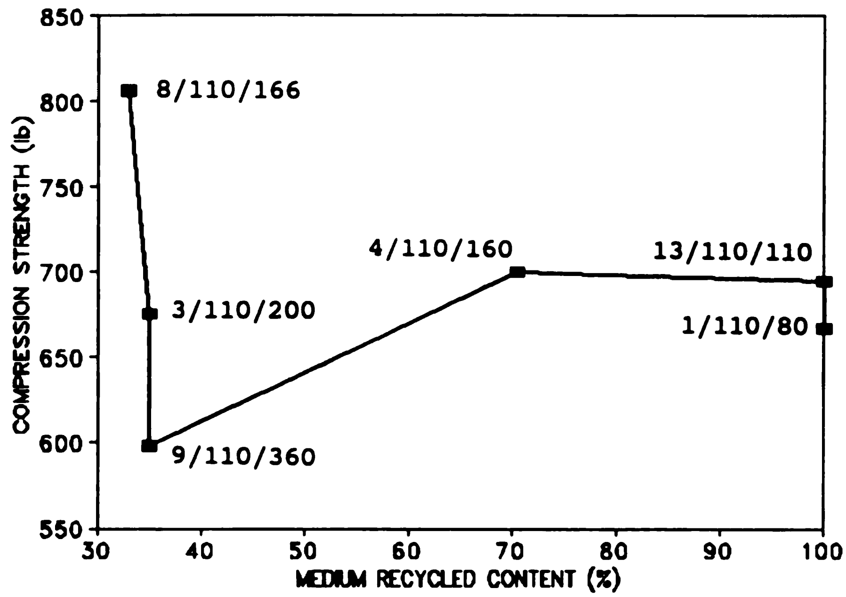

Figure 12: Box compression strength versus medium recycled content for a 110 lb/1000 ft^2 board basisweight at TAPPI standard conditions

lack of the expected trend in compression strength: the accuracy of the recycled content quoted by the manufacturer, and the board manufacturing process itself. According to Mr. Ralph A. Young, an expert in the manufacture of corrugated board, the recycled content of a run of board on any given day can vary tremendously (Personal Communication, 1992). The values quoted are average taken over very long time periods of up to a year. In addition, identical boards from distinct maufacturers can produce boxes with very different compression strengths even if the medium and linerboards had the same recycled contents and basis weights. This makes sense because there are many variations in the manufacturing process which can occur such as the amount and type of glue, web tension, liner/medium contact pressure, line speed, etc. The adhesive used and the strength of the bond are obviously important. In addition, fiber type has an affect strength of the board. It has been found that the addition of Old Corrugated Containers (OCC) to the furnish alone has improved the strength properties of the board (Huck, 1991: pg 23, Uutela and Black, 1990: pg 51, and Horn, Bormett and Setterholm, 1988: pg 146). Therefore, added OCC may lead to dissimilarities in box compression strength.

What is needed in order to establish the effect of the manufacturing process on board strength is a comparison of compression strength results for boards with identical basis weights and recycled contents made by two different manufacturers. Unfortunately this comparison can not be made with the available data. There are however two pairs of boards which compare very closely and are produced by different manufacturers. In Table 1, boards 1 and 13 have identical basis weights and nearly identical recycled contents. The recycled contents of the liners differ by only 10% and this should not matter any way because the medium is the important factor in compression strength. From Table 2 and 14, the compression strengths are 667 lbs for board number 1, and 695 lbs for board number 13. Given the variation in data for these boards, the logical conclusion is that the manufacturing process did not make a difference in compression strength. Likewise, in Table 1, boards 3 and 8 are made by different manufacturers and have identical basis weights and very similar recycled contents. From Tables 4 and 9, the compression strengths are 675 and 806 respectively. However due to the wide variation in data, no definite conclusion can be reached regarding the effect of the manufacturing process.

II. COMPRESSION STRENGTH VERSUS EDGE CRUSH RESISTANCE

Box compression strength can be predicted from edge crush resistance by the Mckee formula. One of the objectives of this study was to compare the predicted strength to the actual strength. Table 17 shows the compression using the actual edge crush strength from the tests. The standard deviation on predicted strength is due to the standard deviation on edge

Table 17: Predicted box compression strength versus actual compression strength. Values listed are mean/standard deviation.

board no.	edge crush (lb/in)	predicted compression strength (lb)	actual compression strength (lb)
1	40.8/2.0	709/35	667/40
2	28.8/2.1	500/36	727/84
3	23.1/2.2	401/38	675/100
4	34.2/2.9	594/50	700/79
5	36.7/3.2	637/56	770/111
6	39.0/3.9	677/68	586/70
7	37.0/2.2	643/38	713/91
8	40.0/5.1	695/89	806/83
9	34.3/3.9	596/68	598/179
12	32.6/2.4	566/42	643/61
13	35.5/2.6	617/45	695/57
15	48.0/2.1	834/36	770/106

crush strength. The predicted box compression strengths decrease proportionally as edge crush resistance decrease but this is not always true for the actual box compression strength. Figure 13 shows the relationship in graphical form. According to this figure, there was no linear correlation between box compression strength and edge crush resistance as implied by the McKee formula. This may be due in part to the fact that the test boxes were hand made and in part to the fact that a simplified version of the McKee formula (see Literature Review, section of Edge Crush) was used. For example, the height of the test box is not reflected in this version of the McKee formula. It is known that two boxes that differ only in height give dissimilar compression strengths. The taller the box height, the lower the compression strength. Therefore, it is possible that the McKee formula needs more parameters when recycled board is used.

III. PROPERTIES VERSUS RECYCLED CONTENT

Figures 14-17 and Table 18 show the various board properties graphed against recycled content. Each board property like edge crush, flat crush, puncture, and burst strength is influenced most by either the medium or the linerboard. Edge crush and flat crush strength are influenced most by the corrugating medium while puncture and burst strength are influenced by the linerboard. Therefore, the edge crush and flat crush resistance are plotted against medium

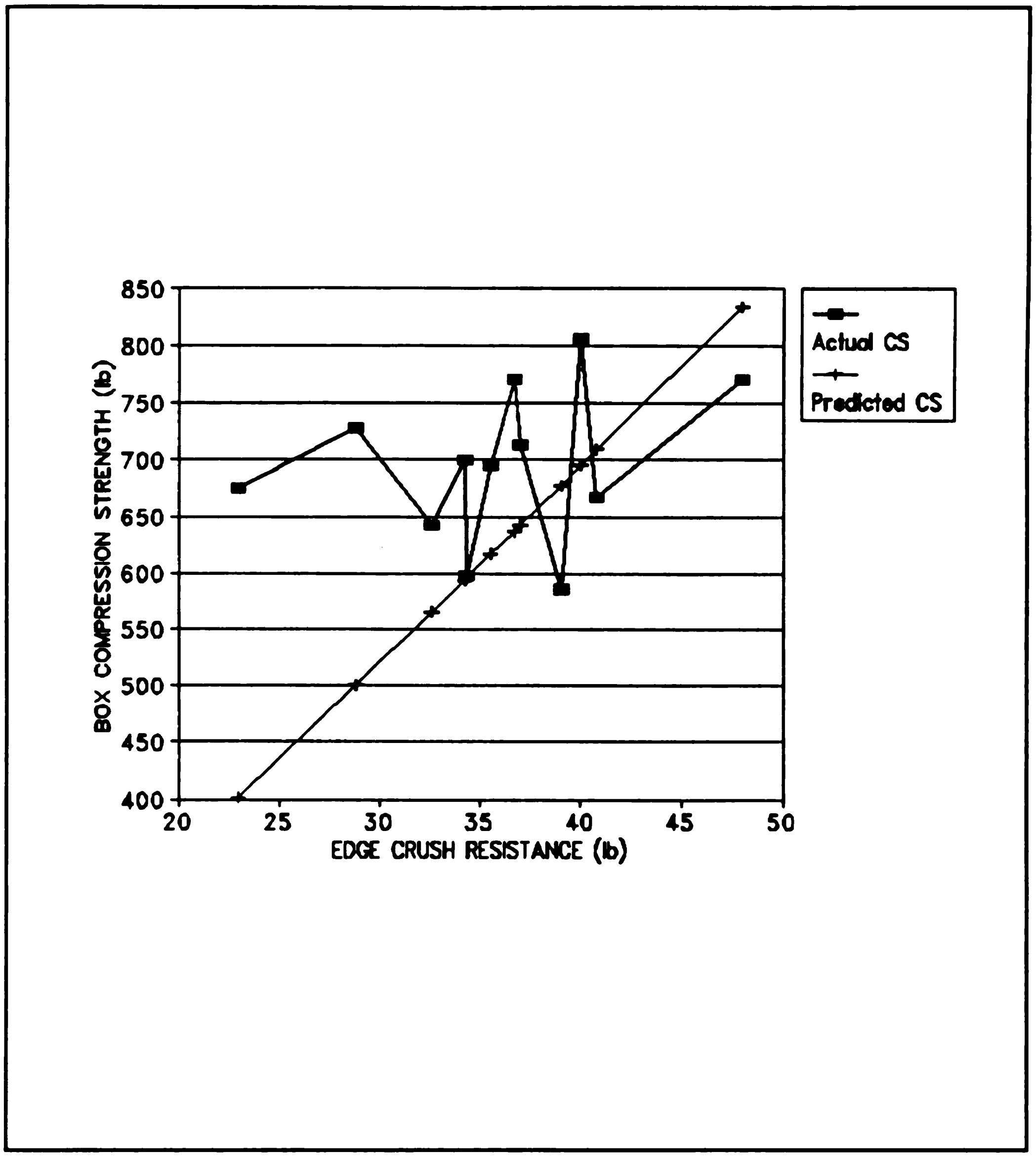

Figure 13: Actual and predicted box compression strength versus edge crush resistance at TAPPI standard conditions

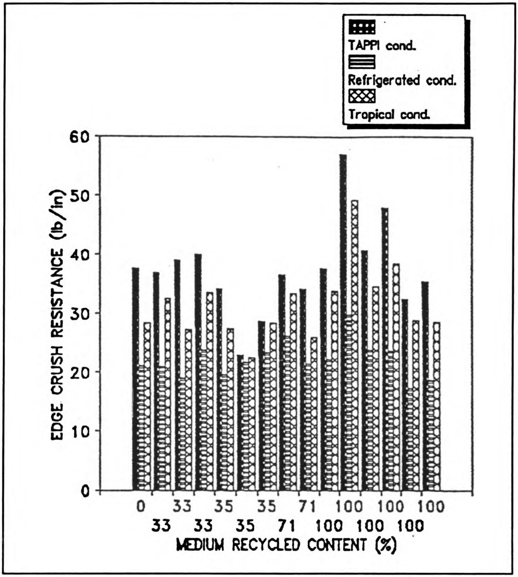

Figure 14: Edge crush resistance versus medium recycled content for three humidity conditions

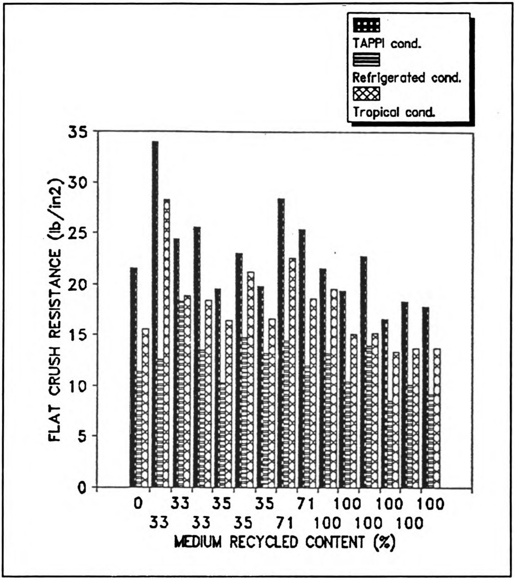

Figure 15: Flat crush resistance versus medium recycled content for three humidity conditions

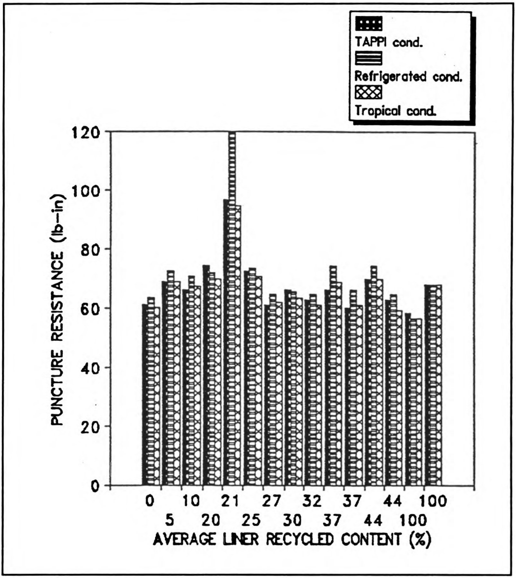

Figure 16: Puncture resistance versus average liners recycled content for three humidity conditions

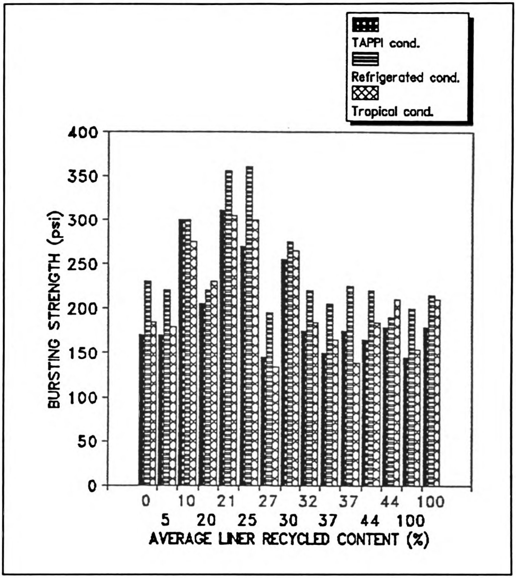

Figure 17: Bursting strength versus average liners recycled content for three humidity conditions

Table 18: Values listed are mean/standard deviation for pin-adhesion strength of the 15 board types for three humidity conditions

Board No.	Pin-adhesion strength (lb/in)		
	Tappi Cond. 73°F and 50%RH	Refrigerated Storage 41°F and 85%RH	Tropical Cond. 104°F and 85%RH
1	58.6/4.2	41.0/4.1	40.8/6.0
2	45.7/6.3	47.6/2.5	45.5/2.5
3	56.9/3.5	44.4/1.1	47.4/1.5
4	52.0/5.9	51.7/6.1	53.1/2.4
5	46.7/5.8	46.3/2.0	48.0/4.4
6	42.4/6.4	42.1/2.4	47.8/5.0
7	48.1/2.2	35.4/2.4	43.3/4.6
8	51.6/8.2	35.2/4.5	44.2/3.4
9	36.1/9.6	31.8/1.2	41.6/2.5
10	40.0/1.5	36.4/3.1	32.9/4.2
11	47.2/4.7	44.8/1.9	55.2/4.1
12	50.0/2.9	40.7/2.7	46.7/3.0
13	45.9/4.2	38.6/2.2	40.2/3.6
14	56.0/3.1	42.5/1.8	47.6/2.4
15	50.0/1.7	33.9/6.7	41.3/1.9

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recycled content and puncture resistance or burst strength are graphed against linerboard recycled content. For pin-adhesion which measures bond strength, failure of the corrugated board can be the cohesive, adhesive or substrate failure. It therefore makes sense to plot pin-adhesion strength against recycled content only if the failure is cohesive since this would then be influenced by recycled fibers. Since the type of failure was not determined during the tests, no such plot can be made. As with compression strength, there appears to be no definite trend, possibly due again to differences in manufacturing processes and the specific mix of recycled contents and types.

IV. PROPERTIES VERSUS MOISTURE CONTENT

Figures 14-17 and Table 18 also show the relationship between strength properties and moisture content. In general, as moisture content increased, strength decreased. The condition which produced the least moisture content in the board was the TAPPI standard condition. The condition which produced the greatest moisture content was refrigerated storage even though the tropical condition had the greater absolute humidity due to the fact that the temperatures was higher and the relative humidity was the same. The reason for this is that even though the tropical environment exerted a greater vapor pressure and hence tended to drive more moisture

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into the board, the solubility of water in the board was decreased at this elevated temperature. Consequently, the board absorbed less moisture even though there was more moisture present.

In order to investigate the strength of the correlation between the various board properties and moisture content, linear regression was applied to the data in Figures 14-17 and Table 18 separately. The results are given in Table 19.

Here, EC is the edge crush resistance (lb/in) and MC is moisture content (g H_2O/g dry board). Likewise, FC is flat crush resistance (lb/in^2), PA is pin-adhesion (lb/in), PU is puncture resistance (lb-in), and BS is bursting strength (psi). The correlation coefficient for EC was r^2=0.537 which means that 53.7% of the variation in edge crush resistance could be explained by moisture content. For flat crush, there was a 60.1% (r^2=0.601) variation in flat crush explained by moisture content. Also, there were 27.4%, 1.5% and 9.6% variations in pin-adhesion, puncture resistance and bursting strength, respectively which could be explained by moisture content.

According to the results, edge crush, flat crush, pin-adhesion, puncture and bursting strength were negatively influenced by moisture content. As moisture content increased, strength decreased. Puncture and bursting strength were positively influenced. However, all of the correlation coefficients were less than 0.9, which means that linear correlation was poor. This is especially true for puncture and

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Table 19: Linear regression between Edge Crush (EC), Flat Crush (FC), Pin-adhesion (PA), Puncture Strength (PU), Bursting Strength (BS), and Moisture Content (MC) for all 15 board types.

properties	Linear regression	r^2
Edge crush (lb/in)	EC = 51.6 - 1.9*MC	0.537
Flat crush (lb/in^2)	FC = 32.0 - 1.3*MC	0.601
Pin-adhesion (lb/in)	PA = 56.1 - 1.0*MC	0.274
Puncture strength (lb-in)	PU = 64.7 + 0.4*MC	0.015
Bursting strength (psi)	BS = 157.6 + 5.4*MC	0.096

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CONCLUSIONS AND FUTURE RESEARCH

The results of this study were:

1. There was no definite trend between box compression strength or board properties and recycled content due most likely to wide variations in data, differences in manufacturing processes, and the mix and type of recycled boards.
2. There was no definite trend between actual box compression strength and edge crush resistance when recycled board was used. The actual compression strengths were not predicted accurately by McKee formula.
3. Refrigerated conditions produce the highest moisture content in the the recycled boards. An increase in moisture content produced a decrease in edge crush, flat crush and pin-adhesion but an increase in puncture resistance and bursting strength. The low correlation coefficients however make these results questionable.

A more detailed study needs to be carried out to compare recycled boards with no differences in basisweight and recycled content in order to evaluate the effects of different manufacturing processes on strength. A separate study should also be done on boards with different recycled contents made by the same manufacturer. In this way, the effect of recycled content can be evaluated conclusively.

APPENDIX

APPENDIX

Box compression strength can be predicted using McKee's equation as follows:

$$CS = 5.87*ECT(ZH)^{1/2}$$

where: CS = top-to-bottom compression strength, in lbs

ECT = edgewise compression, in lbs/in

Z = box perimeter (2L+2W), in inches (56 inches)

h = board caliper, in inches (5/32 inches for C-flute)

Since ECT affects CS in a linear way, from McKee formula, the standard deviation on predicted CS can be determined from the standard deviation on ECT.

Sample Calculations:

Board No.1; $CS = 5.87*(40.8\pm2.0)(56*5/32)^{1/2}$

$= 743-674$ lb or avg = 709 lb

SD of predicted CS= $(2.0/40.8)*709 = 35$

so $CS = 709\pm35$ lb

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