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Relative Humidity Effects on the Compression Strength of Corrugated Boxes

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RELATIVE HUMIDITY EFFECTS ON THE COMPRESSION STRENGTH OF CORRUGATED BOXES

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ABSTRACT

Corrugated boxes are relatively inexpensive and used extensively to contain and protect consumer products as they move through the distribution system, providing a much-needed function in today's economy. Also, corrugated boxes are constructed from paper, which is affected by ambient moisture in the atmosphere. Relative humidity regularly varies between 30 to 90 percent depending on location and time of year. Above a relative humidity of 30 percent, paper fibers are affected, resulting in a decrease in the top-to-bottom compression strength of corrugated boxes. Therefore, understanding the moisture effect on box compression strength is essential. The goal of this study is to characterize the effect of relative humidity and, subsequently, the effects of moisture content on the compressive resistance of corrugated board boxes. A total of 3,000 industry supplied boxes are used to evaluate moisture content and compressive strength at seven relative humidity conditions from 30 to 90 percent. Three sets of conditions are repeated to test repeatability for a total of ten batches tested overall. Preconditioning and conditioning of all specimens meet or exceed the requirements of TAPPI T402. All specimens are compression tested by following TAPPI T804. Further, all compression testing is performed in an environmental chamber at test conditions to ensure uniformity. The moisture content for three out of every ten specimens is recorded using a loss-upon-drying moisture balance. Results indicate a second-order polynomial increase in moisture content as a function of relative humidity. The compression strength of corrugated boxes is found to vary linearly with moisture content for the range tested and follows a second-order polynomial decrease with increasing relative humidity. The data from this study are compiled into a table of corrugated box strength reduction factors for comparison with the results from previous studies.

DEDICATION

I dedicate this thesis to my Mom, Dad, twin brother Michael, and my Grandparents.

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First and foremost, I would like to thank God Almighty for giving me the strength, knowledge, ability, and opportunity to undertake this research study and the perseverance to complete it satisfactorily. Without His blessings, this achievement would not have been possible. - Praise the Lord!

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TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

List of Figures (Continued)

Figure Page

CHAPTER ONE

INTRODUCTION

For over a hundred years, corrugated fiberboard boxes have been used to contain, store, and transport many packaged goods because they are lightweight, inexpensive, and made from renewable sources (Maltenfort, 1988). Wooden crates are an alternative to corrugated boxes; however, they are expensive and heavy in comparison. At the end of World War I, wooden crates used to transport goods accounted for 80% of the material, with fiberboard boxes making up the remaining 20%. At the start of World War II, this ratio had flipped, with only 20% of goods shipped in wooden crates (Maltenfort, 1988).

In 2017 the paper segment of the North American containers and packaging market accounted for 30.8 billion dollars (MarketLine, 2018). As such, fiberboard corrugated boxes are essential and vital to today's economy.

The purpose of this study was to test the effect of relative humidity, and subsequently, the effect that moisture content within the corrugated board has on the top-to-bottom compression strength of corrugated boxes. In the course of this study, the Fibre Box Association (FBA) coordinated the donation of an assortment of single and double wall corrugated box specimens from various box manufacturers within the corrugated industry. The FBA's intent was that the boxes would act as a representative sampling of boxes from across the industry. Thus, specific variables, such as recycled content and board flute/liner caliper, remained unknown to the researchers at Clemson University.

Seven different relative humidity conditions, ranging from 30% to 90% relative humidity, were used to condition test specimens before compression testing. Three different relative humidity conditions were repeated to test for repeatability. Industry accepted standards for conditioning and testing were followed throughout this study. Atmospheric conditioning times used for this study met or exceeded the recommended times called for in the relevant testing standards, most importantly, to ensure that specimens were at the conditions specified. Additionally, the moisture content of the fiber boxes was determined to relate moisture content to relative humidity and loss of compression strength.

The objective of this study was twofold, first to investigate the relationship between relative humidity and percent moisture content for typical corrugated boxes, and second to study how the compression strength of corrugated boxes varies with percent moisture content and relative humidity.

CHAPTER TWO

REVIEW OF LITERATURE

In this chapter, paper connection to corrugated boxes, and the structure of corrugated boxes is investigated. Next, the interaction of moisture with paper products is discussed, beginning with facts about paper and its interaction with relative humidity. An example of an “average” environment is presented as a humidity hazard. The phenomenon of hysteresis and its impact upon testing of paper-based products also is discussed. Loss in compression strength and the factors involved are also covered, including standards used for testing. Lastly, an overview of the different methods of measuring the moisture content within paper is provided.

2.1 Paper and its Connection to Corrugated Boxes

The *Encyclopedia of Science and Technology* defines paper as a material in sheet form comprised of cellulose fibers (Holik et al. 2012). Dawn (1987) further states that paper is a composite, and the plant fibers mostly consist of lignin, cellulose, and hemicellulose. Sulfate (Kraft) chemical processing is one of the processes used to produces paper fibers. Kraft paper fibers are least damaged by this process and are thus stronger (greater compressive strength) than other paper fibers produced by other processes (Marcondes, 1994). As a result of this, corrugated boxes are commonly made from Kraft paper. It takes multiple sheets of paper to make a corrugated box, which consists of a liner (sidewall) and a corrugated section glued between the liner material(s). The corrugated part is called the medium (or flute) and has an arched shape (Maltenfort, 1988).

2.2 Corrugated Boxes Provide Protection Through Structure

The corrugated box is useful as it can withstand compressive loads and protect products; this is especially true of boxes stacked on a pallet, where the bottom-most box must support the weight of boxes above it (Scott, Abbott, & Trosset, 1995). Furthermore, this enables safe shipment throughout a distribution system. The compressive strength of corrugated boxes is attributed to the stiffness of the paper and is enhanced by the arched shape called flutes (or medium). Two distinct structures comprise corrugated boxes, an arched fluted material, and a liner. The thickness of the paper (also known as caliper) used for the flutes and liner can vary (Scott et al., 1995). There are five different standard flute sizes of corrugated board, Fig. 2.1, that are sized by average wall thickness and an average number of flutes per foot, Table 2.1 (Fiber Box Handbook, 2015). For a majority of corrugated boxes, liners are glued by a starch-based adhesive to a fluted paper layer. Single-face, single-wall, double-wall, and triple-wall are the four common combinations of wall and fluting used in the packaging industry (Soroka, 2002). Single-face corrugation is comprised of one single liner material and one fluting material, whereas single-wall (also called double-face) corrugated consists of two liners and one fluting structure glued between them. For example, if a box had the requisite average of flutes per foot, such as 47, it would be called B-flute single-wall. Double-wall boxes are constructed with one additional liner and fluting, and triple-wall again adds another liner and fluting.

Table 2.1: Flute Average per Foot (Fiber Box Association Handbook, 2015)

Flute	Average Number of Flutes/Foot
A	33
B	47
C	38
E	90
F	125

The liners and flutes (medium) are glued together by a machine called a corrugator. The box shape, with flaps, slots, and stitch/glue tab is either cut out by this machine or another as part of processing. One common type of box configuration is a regular slotted container (RSC), Fig. 2.2. The flaps of a RSC can either be half the width of the box and meet in the middle when folded, or can be shorter and not; depending upon the box design (Soroka, 2002). The flaps are folded over and sealed to provide containment, and slots are an allowance that grants room for the flaps to effectively close. Glue or stitch tabs allow the opposing sides to be combined, producing a typical corrugated box.

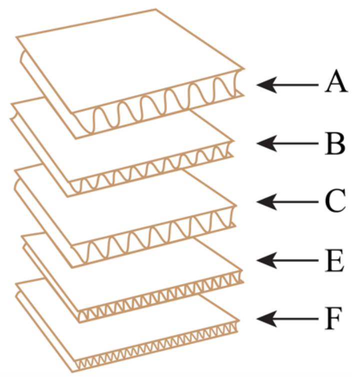

Figure 2.1: Examples of various sizes of corrugated fluting. Reproduced from Fiber Box Handbook, 75th Anniversary Edition (Fibre Box Association, 2015).

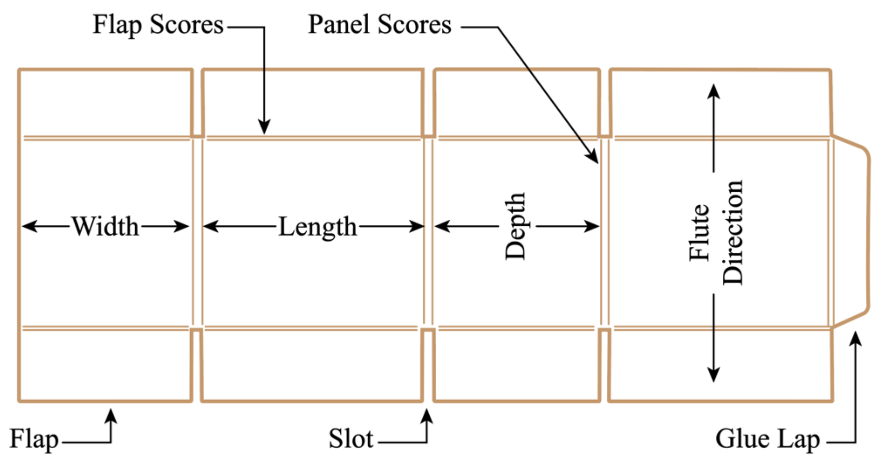

Figure 2.2: Generalized Regular Slotted Container.

Two different types of box structures are depicted in Fig. 2.3: single-wall and double-wall construction. The additional liner and flutes provide multi-wall boxes increased compression strength due to the added material. For ease of reference, multiwall boxes are often referred to as their combined flute types, such that a B-flute and a C-flute made together would be called BC double-wall (Maltenfort, 1988). There is a specific naming structure for the flute positions of multi-wall corrugated boxes; however, for this project, it was not considered and is omitted.

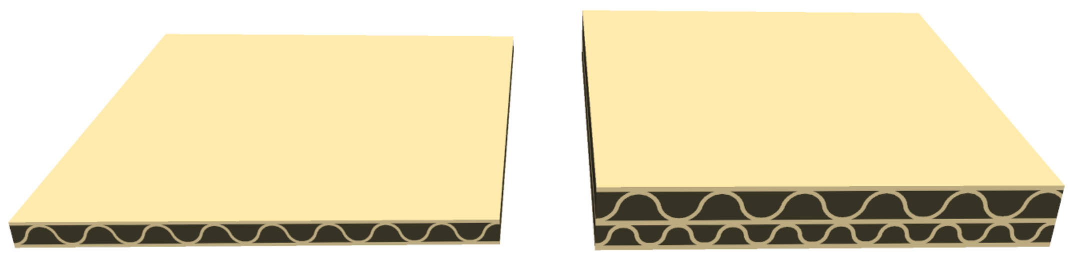

Figure 2.3: Single-wall (left) and double-wall (right) box specimens.

The orientation of the fluting medium can have an impact upon the compression strength of corrugated boxes. Typically, vertical flute boxes, Fig 2.4, are more commonly used than horizontal flute boxes (Maltenfort, 1988).

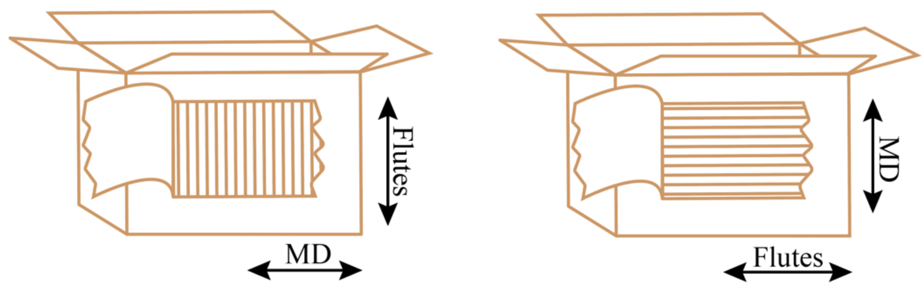

Figure 2.4: Vertical (left) and horizontal (right) flute boxes.

There are three different orientations a box can be stacked; these are top-to-bottom, end-to-end, and side-to-side, Fig. 2.5. If the boxes' orientation changes, the flute direction and where the manufactures joint may change too. For example, an RSC box with vertical flutes, stacked in the end-to-end orientation, will not have flutes in the vertical direction. Single boxes can be transported and stored in any orientation (Maltenfort, 1988). Therefore, a box needs to have the appropriate level of compression strength to protect the product in all directions.

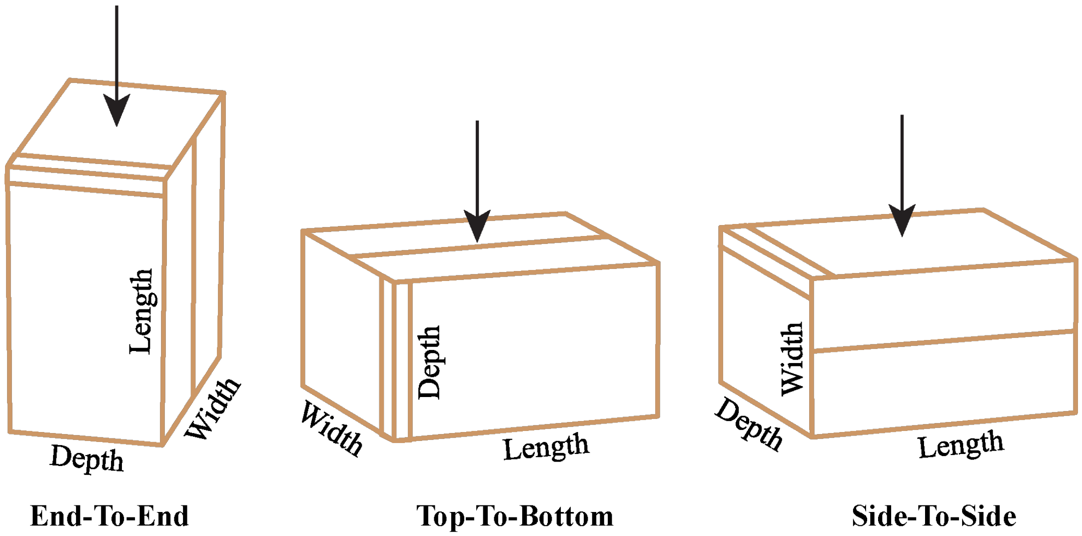

Figure 2.5: Possible box stacking orientations.

2.3 Paper and Moisture

The central core of paper fibers are hollow and, along with the fiber walls, have room available for water molecules. As a result, paper has an affinity for water molecules present in the atmosphere and is classified as a hygroscopic material. Paper will readily absorb and release this moisture to be in equilibrium with the environment it is in. When paper absorbs water molecules, the fibers swell and gain weight. Fiber swelling can be 15-20 times more so in the girth as opposed to length. The fiber-to-fiber bonds, which are the interconnecting bonds within paper, are affected by moisture. As moisture content rises, paper becomes less stiff and results in a change in mechanical behavior (Scott et al., 1995).

2.4 Humidity Hazard

Warehouses often provide protection from rain, however, they are not always climate controlled, and, thus, the temperature and relative humidity will acclimate to the outside environment. It is typical for the ambient relative humidity in the United States to fluctuate in the course of a 24-hour period, depending on weather conditions. Figure 2.6 depicts relative humidity data from a weather station located at the Greenville-Spartanburg International Airport for October, 2018 (NOAA Weather Station Raw Data, 2019). In this example, during the day, relative humidity (RH) fluctuates from an average low of 40% RH to a high of 95% RH, with extreme lows of about 25% RH and highs of 100% RH. Granted, this was during a time of frequent precipitation. In the course of storage and transport of a package, there is a high likelihood that corrugated boxes will be exposed to a wide range of relative humidities.

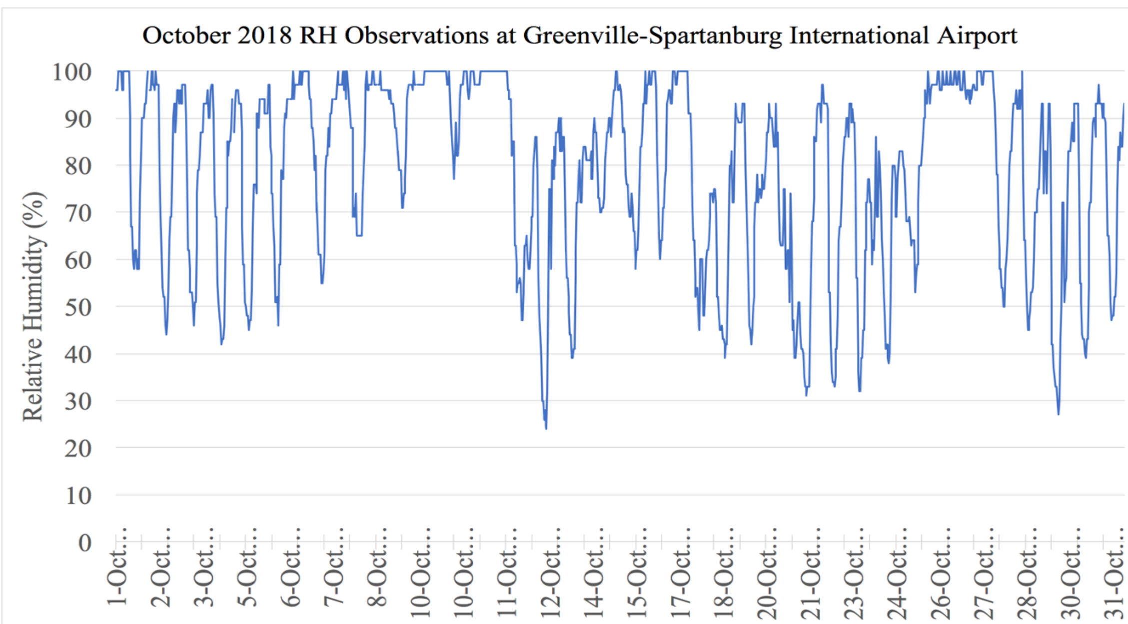

Figure 2.6: Relative Humidity Observations at Greenville-Spartanburg International Airport, October 2018 (NOAA Weather Station Raw Data).

The *Encyclopedia of Weather and Climate* defines relative humidity as "the ratio of the mass of water vapor that is present in a unit mass of dry air to the amount that would be required to produce saturation in that air" (Allaby, 2002). When the temperature reaches the dew point, the air is saturated with water vapor, and relative humidity reaches 100%. Temperature must be taken into account when calculating relative humidity, as this affects the capacity of the air to hold moisture in the form of water vapor. For example, at freezing temperatures, there is less available water-vapor "capacity" in the atmosphere than that of hotter temperatures near 35°C (95°F) (Allaby, 2002). The common paper industry-accepted testing conditions are called standard conditions and are defined as 23 $\pm$ 1°C and 50 $\pm$ 2% relative humidity.

2.5 Moisture Sorption Hysteresis

Paper is affected by a phenomenon called hysteresis (Wink, 1961). Hysteresis is defined as "a phenomenon wherein two (or more) physical quantities bear a relationship which depends on prior history" (Huntington and MacCrone, 2012). In this case, moisture content has an effect upon the physical properties of paper and corrugated boxes with relation to previous moisture histories. In other words, it takes time for paper to react to moisture in the environment.

The conditions that affect how the substrate behaves are set upon the first drying cycle experienced by paper. This establishes the adsorption (moisture uptake by paper from the environment) and desorption (release of moisture by paper to the environment) patterns, usually plotted as curves (moisture content versus relative humidity) that the paper will follow for hysteresis throughout its lifetime. Figure 2.7 is a general plot depicting the adsorption and desorption curve for paper published by Wink in 1961.

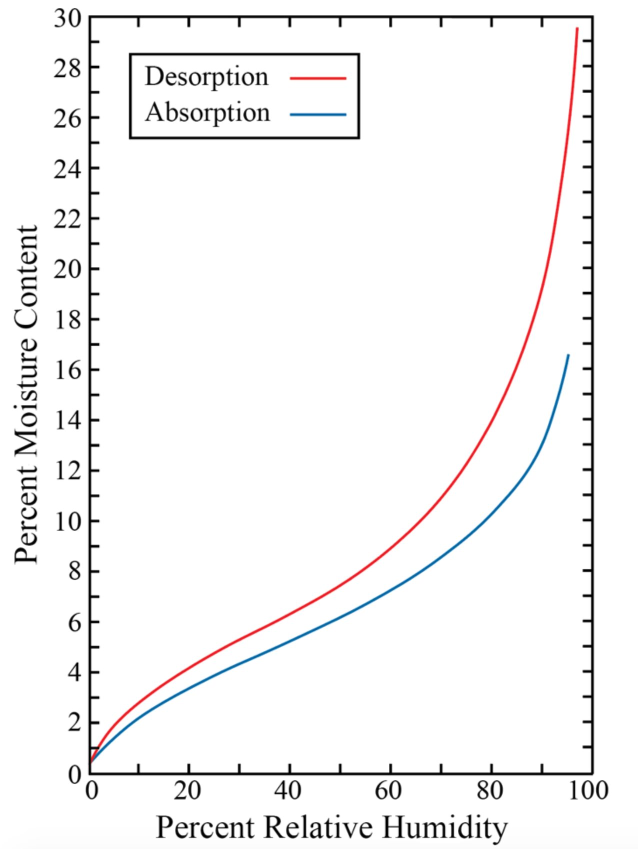

Figure 2.7: General desorption and adsorption curves. Reproduced from The Effect of Relative Humidity and Temperature on Paper Prosperities, TAPPI (Wink, 1961).

As discussed previously, one can observe that the moisture available within the paper is different depending on prior moisture history. The desorption curve was made from a specimen pre-conditioned at higher relative humidity, and the adsorption curve is from a specimen pre-conditioned at a lower relative humidity (Wink, 1961). Because the two curves are not the same, this indicates there is a measurable difference between absorption and desorption behavior. Therefore, hysteresis does have an impact on the testing of paper and corrugated boxes and must be mitigated. If paper were not affected by hysteresis, then there would be only one curve for absorption and desorption.

Wink found that the effect of moisture hysteresis on the physical properties of paper is several times greater than that of temperature or relative humidity and can account for significant variability of test results. He also found that the effect of hysteresis can be mitigated by preconditioning in a dry atmosphere, specifically, at 30% relative humidity (Wink, 1961). This finding is consistent with the current Technical Association of the Paper and Pulp Industry (TAPPI) testing standard, T402: *Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and Related Products*. In this standard, preconditioning is recommended in a relatively dry environment (10-35% relative humidity) and temperature between 22 to 40°C (72-104°F). This preconditioning is then followed by conditioning at the desired test condition (TAPPI T402, 2016).

2.6 Paper Stiffness Loss due to Relative Humidity

As discussed earlier, paper, and subsequently corrugated boxes are susceptible to the effects of relative humidity because paper will readily absorb or desorb available moisture in the air to be in equilibrium with its environment (Frank, 2014). As an example, a piece of paper with its moisture content at equilibrium and placed in a more humid environment will gain moisture from the new environment until it reaches equilibrium with the new environment. Uldis determined that corrugated board will be within 70 percent of its environment after 18 hours of being placed within that environment (Uldis, 1977). Subsequently, TAPPI recommends conditioning for 24 hours to give the substrate the time to reach equilibrium before testing (TAPPI T402, 2018). ASTM International is one of the organizations that produce the specification and testing standards used in many industries, including packaging. ASTM test standard D4332 *Practice for Conditioning Containers, Packages or Packaging Components for Testing*, does not explicitly state a time frame for preconditioning; only that sufficient time should be given for the product to come into equilibrium before testing. If no specific conditioning time is stated, then at least 72 hours of conditioning should be done (D4332, 2001).

The International Safe Transit Association (ISTA) is an organization dedicated to the safe distribution of packaged goods, by way of a variety of standards for package testing. ISTA recommends users know and measure their distribution environment's hazards, including the temperature/relative humidity encountered by their packaging. A majority of ISTA test procedures require preconditioning at the testing laboratory's ambient temperature and humidity (defined as the conditions of the lab during testing) for 6 hours or 12 hours before testing. However, some ISTA test procedures require or provide the option for specific conditioning 72 hours before testing. There is an exception to this that specifies 72-hour conditioning at hot, humid conditions then 6-hour conditioning at extreme heat and moderate relative humidity (ISTA, 2018).

The mechanical properties of paper include burst, tensile, tear, fold (fold endurance), and stiffness. Burst refers to the ability to resist pressure applied to one side, and tensile is defined as stretching from opposing forces. A tear refers to the breaking or a cut in the material. Fold endurance is the ability to bend without breaking. Stiffness, specifically "flexural stiffness", is defined as resistance to bending, and, in a packaging context, it is also known as resistance to compressive deflection (Scott et al., 1995). Figure 2.8 depicts how these properties are affected by relative humidity. It should be noted that many of the parameters vary with relative humidity in a non-linear way and experience a maximum. The exception to this is tear and stiffness, which are closer to linear. Stiffness decreases with increasing relative humidity and is the most important to corrugated boxes, as it is directly related to the ability of corrugated board to withstand compressive loads. The corrugated structure and the stiffness of the papers used to construct the board are what give corrugated boxes their compressive strength. As relative humidity increases paper stiffness is reduced (Scott et al., 1995).

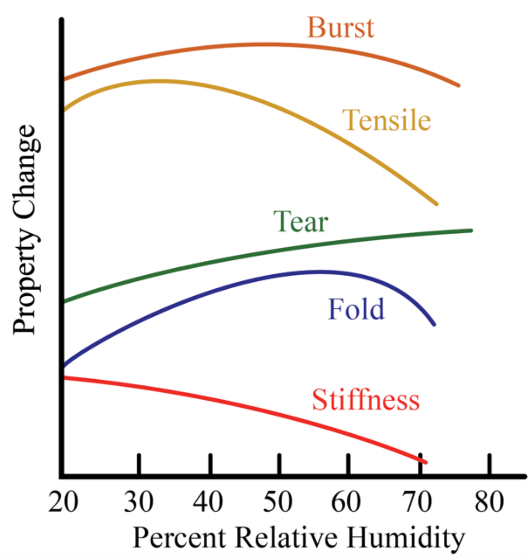

Figure 2.8: Relative humidities effects on the properties of paper. Reproduced from Properties of Paper: An Introduction (Scott et al., 1995).

2.7 Corrugated Box Loss of Strength due to Relative Humidity

As part of Kellicutt and Landt's study investigating the effect of moisture upon corrugated boxes, four different kinds of A and B-flute boxes were tested at varying environmental conditions ranging in temperature from -8.9°C to 26.7°C (-20°F to 80°F) and at 30, 65, 80, and 90 percent relative humidity. The authors did not disclose the total number of specimens tested, preconditioning performed, conditioning time, or method of sealing the flaps on the test boxes. The test load was selected as various percentages of the top-to-bottom box compressive strength (BCT) value, (58, 78, 87, and 95 percent). The researchers designed a test apparatus to distribute the load on the corrugated box evenly via a swivel platen at a rate of 10.2 mm/min (0.4 in/min). This allowed them to test all panels of the box. The resulting data was plotted, Fig. 2.9, which depicted a negative slope, demonstrating that the compression strength of the corrugated box decreases as percent moisture within the fiberboard increases. An average trend line (represented by the red dotted line) was fit to the manually plotted data (blue solid lines) on a semi-log graph, and the slope was determined to develop a model, Eq. (1) that could be used to predict the compression strength of a corrugated box at any relative humidity,

$$y = b(10)^{mx} , \qquad \text{Eq. (1)}$$

in equation 1, y is the desired compression strength, b is the compression strength at zero percent moisture content, m is the average slope (determined by the Kellicutt & Landt to be -3.01), and x is the moisture content expressed as a decimal (for example 6.5% is 0.065) (Kellicutt and Landt, 1951). Kellicutt and Landt did not limit their model to any particular style, material, or fluting. However, only A and B-flute corrugated RSC boxes were used for testing.

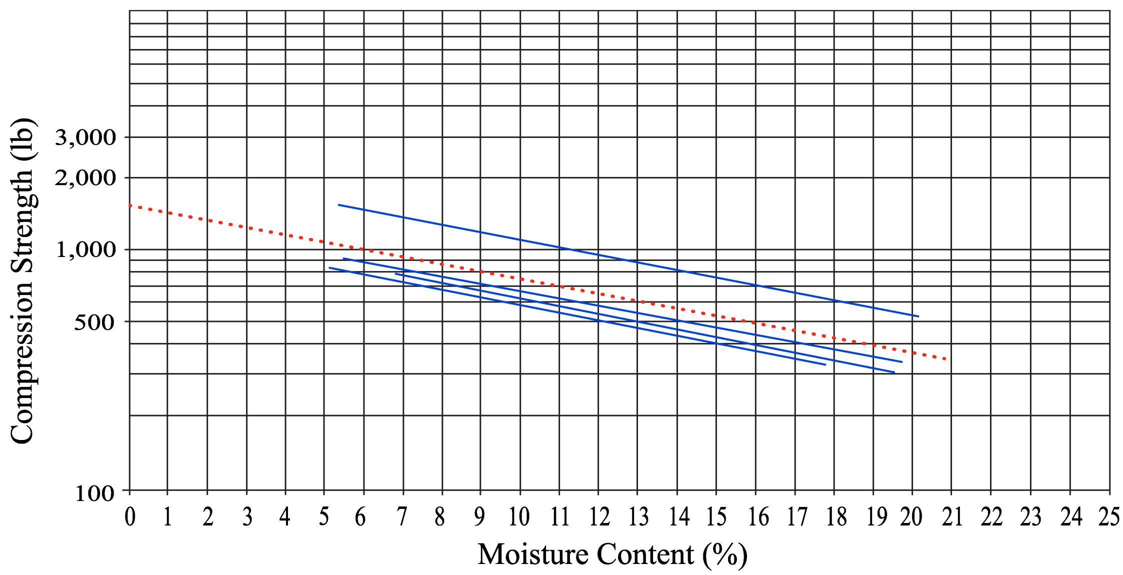

Figure 2.9: Moisture Content Effects Upon Fiberboard Corrugated Boxes. Reproduced from Fiber Containers: Safe Stacking Life of Corrugated Boxes (Kellicutt and Landt, 1951).

A second model, Eq. (2), was also developed to estimate the compression strength of a box at a chosen moisture content, from a known compression strength at a known moisture content,

$$P = \frac{P_1(10)^{3.01M_1}}{(10)^{3.01M_2}}, \qquad \text{Eq. (2)}$$

in this equation, the unknown compression strength of the box is P, P_1 is the known compressive strength of the box. M_1 is the known moisture content of box P_1, and M_2 is the chosen moisture content of the box P (Kellicutt and Landt, 1951).

Fellers and Bränge (1985) investigated the interaction of moisture content in a range of 1% to 23% on a Kraft liner material and a single NSSC-fluted board (Neutral Sulfite Semi-Chemical pulping). All samples were commercially sourced from local manufacturers. The samples used were also subjected to rigorous preconditioning and conditioning for this study. Two preconditioning methods were used. The first, used for adsorption, consisted of exposing samples to hot air for 1 hour at 105°C (221°F), then conditioning the sample to the chosen relative humidity level. The second preconditioning focused on the desorption precondition, which began with samples conditioned to 95% relative humidity and then exposed for 1 hour to steam at about 100°C (212°F). The relative humidity range of interest was 20% to 95%. Both adsorption and desorption of moisture were studied as well as compression strength versus relative humidity for the NSSC-fluted board and liner material. Fellers and Bränge used a STFI (Swedish Test Fibre Institute) short span test to test the strength of the NSSC-fluted board. The STFI test is also covered by TAPPI T826, and is a material test that utilizes flexural stiffness of a 15 mm (0.59 in.) wide sample to predict compression strength of corrugated boxes (TAPPI, T826, 2013). They found that the higher the relative humidity, the worse the corrugated specimen performed. Overall, the authors identified an 8% reduction in compression strength for every 1% rise in relative humidity above 50% (Fellers and Bränge, 1985). The compression testing was on the fluted material, not corrugated boxes. The authors did not disclose certain specifics of the experiment, such as equipment used and the number of specimens tested.

2.8 Determining Corrugated Box Failure in Testing

During testing, it is crucial to determine when a corrugated box has failed accurately, or in other words, is no longer able to support a compressive load. Generally, the first occurrence of substantial buckling (or bowing) of corrugated box panels indicates failure. During these tests, it is common to observe a load-deflection graph, Fig. 2.10 and to watch for the visual indications the box has failed. There can be high and low points on the load-deflection graph until the box fails. Specifically, this is not an overall failure unless it also occurs with a visual indication such as panel buckling or bowing (Frank, 2014).

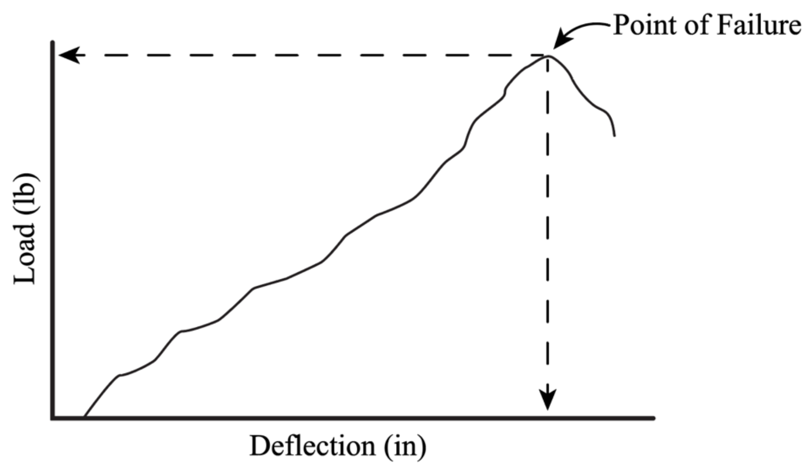

Figure 2.10: Generalized Load-deflection graph. Reproduced from Corrugated Shipping Containers: An Engineering Approach (Maltenfort, 1988).

2.9 Strength Reduction Factor Tables

A strength reduction factor is a predictive value of loss in compression strength at different relative humidities, commonly arranged as a table. These are used by multiplying the total compressive strength of a corrugated box at 50% relative humidity by the strength reduction coefficient at a chosen relative humidity to determine the estimated compressive strength. Prior work considering the effect of relative humidity upon compression strength has resulted in four strength reduction factor tables that include studies by Marcondes (1994), Maltenfort (1988), Hanlon et al. (1998), and the Fibre Box Association (2015) compiled as Table 2.2.

Table 2.2: Combination of strength reduction factors from literature.

RH (%)	Strength Reduction Factors			
	Marcondes (1994)	**Maltenfort (1988)**	**Hanlon (1998)**	**FBA (2015)**
dry	-	-	1.20	-
25	-	1.13	1.10	-
30	-	1.11	-	-
40	-	1.06	-	-
50	1.00	1.00	1.00	1.00
60	0.85	0.93	-	0.90
70	0.70	0.85	-	0.80
75	-	0.81	0.85	-
80	0.55	0.76	-	0.68
85	-	-	0.70	-
90	0.40	-	0.60	0.48
95	0.33	-	-	-
100	-	-	-	0.15

To use Table 2.2, the compression strength of corrugated boxes at 50% relative humidity must first be known. This specific information can be determined in a testing laboratory. As an example, a box conditioned at 50% relative humidity may demonstrate a top-to-bottom compression strength of 453.6 kg (1,000 lb.). The prediction table suggests that this box, conditioned at a relative humidity of 80%, would demonstrate compression strengths of 249.5, 344.7, 308.4 kg (550, 760, and 680 lb.) (Marcondes, Maltenfort, and the Fiber Box Association) respectively.

Missing from all four studies resulting in these strength reduction factors is the experimental design, the number of specimens used, and preconditioning conditions. Maltenfort states that the data provided for the correction factors table "…were entirely empirical and based on very extensive amounts of data on boxes made from Kraft and recycled fiber liners." (Maltenfort, 1988). Maltenfort does not state the methods used to gather these data, nor does he say the samples used or the exact number of specimens in his book *Corrugated Shipping Containers: An Engineering Approach* (1988). The Fibre Box Association lists a reference for its strength reduction table. However, the source is listed as “USDA Forest Products Lab” (Fibre Box Handbook, 2015). No other details are given. Marcondes (1994) and Hanlon et al. (1998) do not provide sources for the strength reduction factors tables either.

2.10 Industry Testing Standards

As with many industries, standards for paper product testing are used for consistency in laboratory testing. TAPPI is an organization dedicated to the development of standards for the testing of paper and pulp-based products (About TAPPI, 2018). ASTM International is comprised of about 150 committees and 2,000 subcommittees of technical experts that produce standards for use throughout the world in multiple fields (ASTM, 2018). Both organizations publish standards for the testing of corrugated boxes.

2.10.1 Corrugated Box Compression Standards

TAPPI T804: *Compression Test of Fiberboard Shipping Containers* is one of a few different standards used for the testing of corrugated boxes within the United States. Another standard commonly used is ASTM D642. TAPPI T804 includes detailed specifications along with testing tolerances and recommends using a fixed platen testing device that is set to compress at 13 mm (0.5 in.) per minute. Due to manufacturing inconsistencies and other problems associated with corrugated boxes, it is recommended that a preload be applied to “square up” the box. Furthermore, this also resets the zero position before a compression test occurs. Preload is defined as an initial weight applied to a corrugated box. TAPPI T804 recommends either a pre-established preload or 5% of the maximum compression experienced by the corrugated box. The pre-established preload is 223 N (50 lbf.) for single-wall boxes and 446 N (100 lbf.) for double wall boxes (TAPPI T804, 2012). After the preload is applied, the test is conducted to failure yielding strength and deformation. Compressive load at failure is the force that the specimen can resist at failure. Failure can be determined in two ways; reduction in supported weight (generally 10%) or by how much the material is compressed, also known as deformation. Specifically, top-to-bottom failure deformation is 19mm (0.75in), or a value defined by the user as critical. The tolerance of the parallelism of the platens is required to be a maximum of 1 mm (0.04 in.) per 305 mm (1 ft.) in the length and width direction. Securing the flaps of corrugated boxes is important, as this can have an impact on the box's compression strength (Frank, 2014). TAPPI standard T804 states flaps can be sealed by various methods such as hot melt adhesive, cold seal adhesive, clipped, taped, stitched, or a combination (TAPPI T804, 2012). Ideally, corrugated boxes used to distribute goods are sized to fit the product with no extra space securely. However, when testing empty boxes, precautions must be taken to ensure the flaps remain in place. According to Maltenfort, the testing of empty boxes using tape is unsuitable, as the internal flaps will be free to move into the box and provide very little support (Maltenfort, 1988).

ASTM D642, *Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads* is a widely-used test standard for determining the compression strength of corrugated boxes. ASTM D642, by its own accord, is similar to TAPPI T804; however, it differs by allowing a floating platen test in addition to the fixed platen test (ASTM D642, 2000). D642 recommends preconditioning following the guidelines recommended by ASTM D4332, *Practice for Conditioning Containers, Packages or Packaging Components for Testing* (ASTM D642, 2000). In the appendices section of ASTM D642, box closure methods are discussed in greater detail.

2.10.2 Environmental Standards

TAPPI test standard T402; *Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and Related Products*, is a standard that is used to establish and set the preconditioning and conditioning atmosphere for testing paper products. It recommends preconditioning specimens at 22 - 40°C (72 - 104°F) in a 10 to 35% relative humidity environment for at least 24 hours, or until it comes into equilibrium with the environment. After the preconditioning, it recommends conditioning at 23 $\pm$ 1ºC (73.4 $\pm$ 1.8°F) and 50 $\pm$ 2% relative humidity as a standard test condition. However, this does not cover special environments that deviate from the standard. TAPPI T402 recommends using an oven and a balance to test a sample to ensure it comes into equilibrium with its environment by measuring the weight of water absorption (TAPPI, 2013). For example, when a box is subjected to a change in the atmospheric relative humidity, the box weight changes and then stabilizes when the specimen is in equilibrium with its environment. If no time is stated for preconditioning and conditioning, then TAPPI T402 recommends tracking box weight until the specimen is in equilibrium with the environment. However, a general recommendation for conditioning time is 5-8 hours for unsealed boxes and 16 hours for sealed boxes.

ASTM D4332, *Standard Practice for Conditioning Containers, Packages, or Packaging Components for Testing* is a test standard that covers the preconditioning and conditioning of containers, packages, and packaging components. It details the different types of environments that are used for testing, the specific equipment used, and what information about the conditioning shall be reported. For standard atmospheres, preconditioning at a temperature between 20 - 40°C (68 - 104°F) and 10 to 35% relative humidity is recommended, followed by conditioning at a temperature of 23 $\pm$ 1°C (73.4 $\pm$ 2°F) and 50 $\pm$ 2% relative humidity. Within this standard are specifics for special atmospheres, such as cryogenic, that have different recommended temperatures and relative humidities (D4332, 2001). ASTM D4332 does not state a specific amount of time for preconditioning. However, for conditioning, it recommends following the times specified in the particular test. If there is no time stated, then 72 hours of conditioning is recommended (2001).

2.11 Moisture Measurement in Paper and Corrugated Board

Various methods exist to measure moisture in paper and corrugated board. Resistance and capacitance electronic instruments, are contact methods because they require physical contact with a sample to make a measurement. Resistance type of measurement works by measuring the electrical resistance within the material that is affected by absorbed moisture (Wernecke and Wernecke, 2014). Instrument measurements, which are pre-programmed devices, are often fast and easy to use. However, a drawback of using an instrument is that it must be calibrated and typically only measures a small area (Scott et al. 1995). An example of this is a capacitance instrument measurement that is localized within the small space between probes. For non-contact methods, infrared and microwave absorption use infrared light or microwaves focused upon the substrate and a sensor to measure returns and calculate percent moisture (Wernecke and Wernecke, 2014). Drying with a convection oven is another method used and is also known as the loss-on-drying method. The loss-on-drying method uses a balance and a convection oven that heats a pre-measured sample to 105ºC (221ºF) until it stabilizes at a constant weight. The more common method utilized by the corrugated industry is the loss-on-drying method. (Scott et al. 1995). The loss-on-drying method is recommended by TAPPI standard T412: *Moisture in pulp, paper, and paperboard*. Equation 3 is used to calculate the moisture content within paper and corrugated board using the loss-on-drying method.

$$Moisture\ Content\ \% = \frac{weight\ loss\ on\ drying\ (g)}{original\ weight\ (g)}\ x\ 100 \qquad \text{Eq. (3)}$$

CHAPTER THREE

MATERIALS AND METHODS

In this section, the different materials, methods, and equipment used for this project are summarized. Experimental design criteria are included within this section, along with the specific equipment settings, procedures, and standards used for testing. TAPPI standards were followed except for conditioning times, which were extended beyond the recommended time stated in TAPPI T402 to assure equilibrium between the specimen and available atmospheric moisture. The testing phase of this project occurred from March 13, 2018, to December 17, 2018.

3.1 Materials

For this project, a total of 3,000 boxes were tested. A single box is called a specimen, whereas a set consists of ten of the same identical specimens. The sets differ from each other by manufacturers, overall dimensional size, recycled content, and flute. A batch is comprised of 30 different sets. A graphic showing the breakdown of specimens, sets, and batches is depicted in Fig. 3.1. The 30 different box sets used for this project represented a range of various dimensions. Internal boxes ranged in volume from 502 cubic inches to 4,774 cubic inches. The flutes consisted of B and C single-wall, and BC double wall, regular slotted corrugated boxes. The flutes of all specimen boxes were arranged vertically, as depicted in Fig. 2.4. Box material specifications were not revealed to the researchers for this project, but rather a range of different materials was used to represent a typical corrugated box purchaser buying a typical corrugated box.

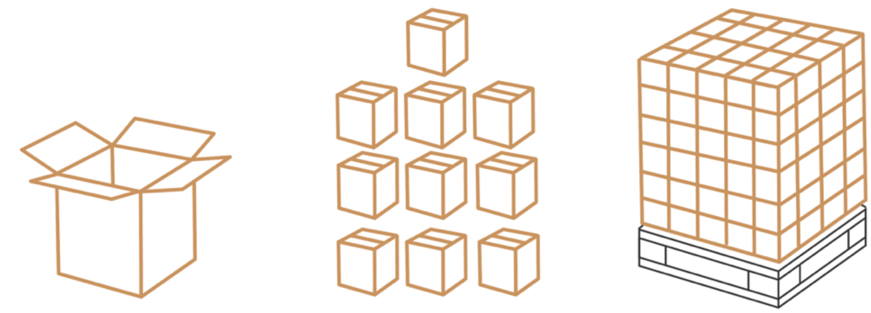

Figure 3.1: Nomenclature of samples. Note: box sizes not to scale.

The boxes tested as part of this study were inspected for visible damage, miss-handling, and manufacturing errors before testing. Specifically, the areas of most concern were the sidewalls of the corrugated box. Those specimens identified as defective were not tested; instead, extra boxes were included with each set so that it did not impact testing. Specific deficiencies that were checked for include water damage, gouges, crushed flutes, and skipped glue lines. Water damage is identified by areas that have been thoroughly soaked with water. Gouges are rips, tears, or holes in the paper of the corrugated box. Crushed flutes are areas where the liners are pressed together, flattening the flutes. Skipped glue lines are areas that lack glue between the liner and flute material.

3.2 Specimen Preparation

All preconditioning was performed in a large, walk-in environmental conditioning chamber, Fig. 3.2. Temperature and relative humidity control were maintained by a Parameter Generation and Control (PGC) (Black Mountain, NC) system (Model: 1080-02). The interior dimensions of this chamber are 3.7 meters long, by 3 meters wide, by 2.3 meters tall (12 feet long, by 10 feet wide, and 7.7 feet tall). The control system was calibrated on July 24, 2017. A setting of 35ºC (95ºF) and 30% relative humidity were used for preconditioning following TAPPI T402 for 48 hours.

After preconditioning, the specimens were moved to the climate-controlled testing room, Fig. 3.3. The specimens were conditioned in the climate-controlled test room for 72 hours before compression testing. The temperature and relative humidity in this room were controlled by a PGC (Black Mountain, NC) unit (Model:9334-4210-91D0000). The control unit was monitored by a Hygroclip (Hauppauge, NY) (temperature and relative humidity) sensor. The first Hygroclip temperature and relative humidity sensor was calibrated and verified to be within specification on June 20, 2018. The first Hygroclip was exchanged for calibration, and a second Hygroclip temperature and relative humidity sensor were calibrated on May 25, 2018. The temperature was held constant at 23 ± 1°C (73.4 ± 2°F) while relative humidity was set at the desired level for testing.

Twenty-four hours before compression testing, the boxes were erected, and the box flaps secured with hot melt industrial carton sealing Ethylene Vinyl Acetate polymer glue (ULine, model number: S-13694).

Figure 3.2: PGC large walk-in environmental chamber used for preconditioning.


Figure 3.3: Inside view of the conditioning/testing room.

3.3 Compression Testing

A Lansmont Corporation (Monterey, CA) Squeezer (Model: 13710), Fig. 3.4, was used for all compression testing of the corrugated specimens and was calibrated on 11/17/2017. The fixed platens measured 762 x 762 mm (30 x 30 in.), and the load cell has a maximum capacity of 2,268 kg (5,000 lb.). The data recorded from this machine was deformation at failure in inches and max force at failure in pounds. The accuracy and repeatability of the load cell is $\pm 1\%$. Compression testing was performed per TAPPI T804, *Compression Test of Fiberboard Shipping Containers*. All boxes were compressed, to the point of failure as described in Chapter 2, Section 2.8, and by the procedures listed in TAPPI T804. The compressive load at failure, the corresponding deformation, and how the box failed (failure mode) were recorded. Seven different relative humidities were used, ranging from 30% to 90% relative humidity to yield a spread of data. The 40%, 60%, and 80% RH conditions were repeated to characterize test repeatability.

Figure 3.4: Lansmont Squeezer used for all compression testing.

Before each day of testing, the parallelism of the platens was inspected. Appendix A contains a detailed description of the method and data used to verify platen parallelism. A preload of 223 N (50 lbf.) was used for single-wall boxes, and a 446 N (100 lbf.) preload was used for double-wall boxes. Specimens were placed within the middle of the compression tester and compressed until failure at a rate of 12.7mm (0.5 in.) per minute. The failure was recorded as either bowing outward or inward. Box failure was determined by watching for signs of damage while also observing the force versus deformation graph generated by the Lansmont Squeezer. An example of the computer output is depicted in Fig. 3.5 and represents a general plot of a corrugated specimen with the maximum compression strength circled in red. The boxes were crushed to at least 10% of their total yield, as suggested in TAPPI T804, and box failure mode was visually confirmed.

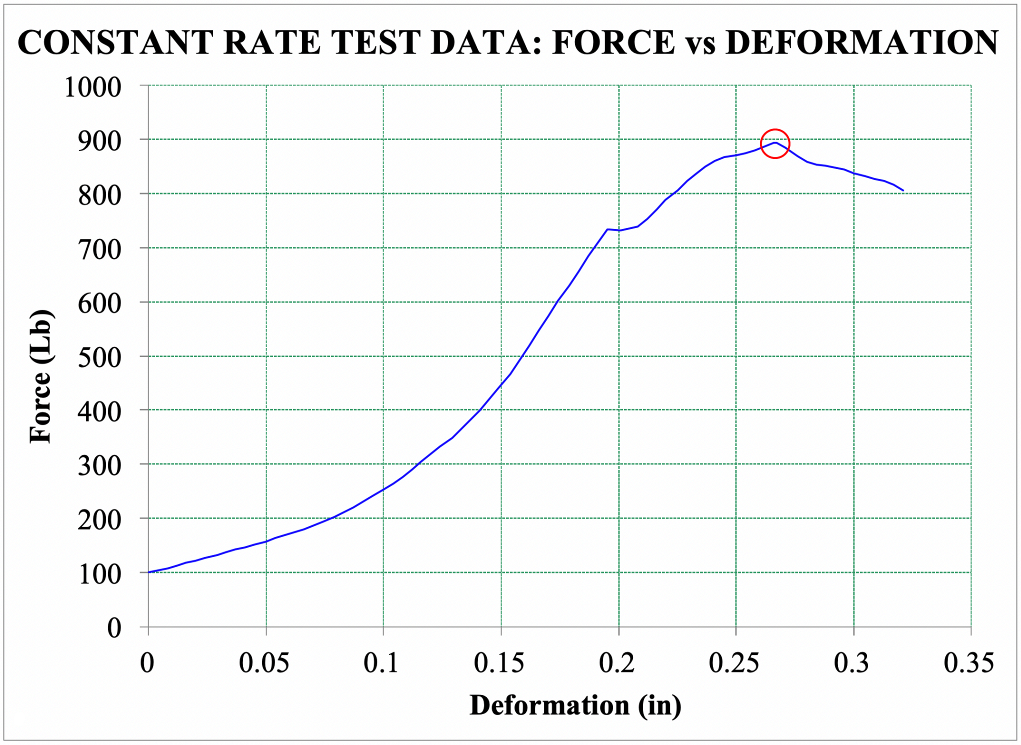

Figure 3.5: Determination of box failure.

3.4 Moisture Testing

Three out of every ten boxes that comprise a set were tested for moisture content by a loss-on-drying moisture balance, Cole-Parmer (Vernon Hills, IL), Fig. 3.6. This device measured the moisture content within the corrugated board as a percentage. The maximum capacity of the moisture balance is 40 grams (0.088 lb), and the readability is 0.001g (2.2×10^{-6} lb). A Hudson Inc (Westmont, IL), safety cutter/flat crush cutter, Fig. 3.7, was used to cut moisture content samples out of the corrugated board after it was compression. The specimen size was 6,452 mm^2 (10 in^2) and neatly fit the sample pans of the loss-on-drying moisture balance. A calibration weight, Rice Lake (Rice Lake, WI), was used to calibrate the moisture balance for each new batch tested as a check that the moisture balance was working correctly.

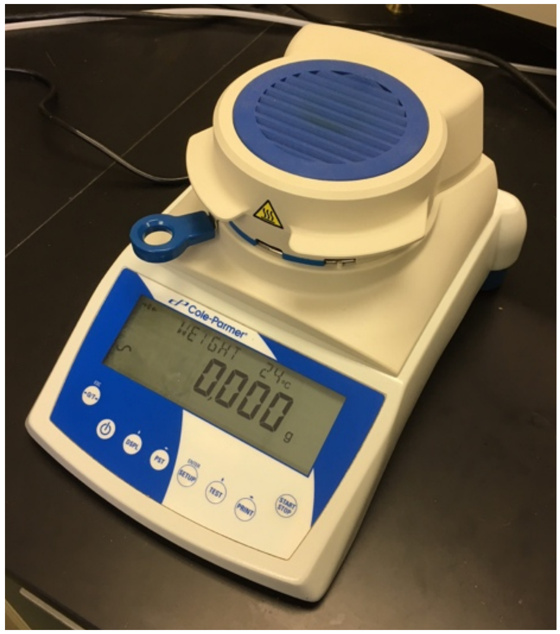

Figure 3.6: Moisture balance used to determine the percent moisture present in the corrugated specimens.

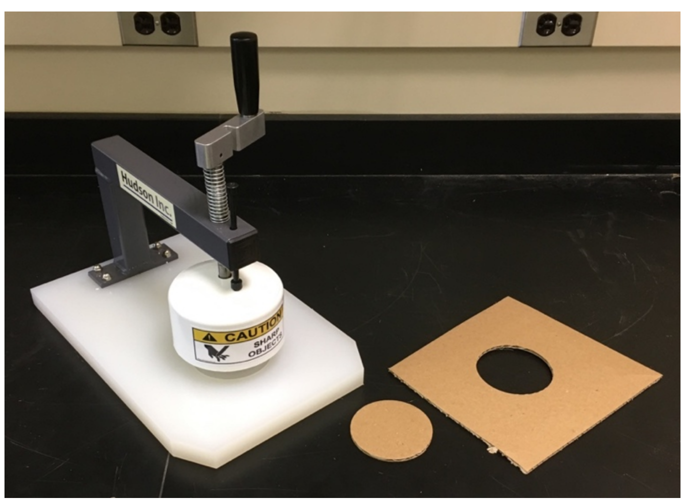

Figure 3.7: Hudson Inc. safety cutter/flat crush cutter.

CHAPTER FOUR

RESULTS AND DISCUSSION

In this section, failure mode observations, repeat batch comparison, outlier treatment, percent moisture content versus relative humidity, relative humidity and percent moisture content effect upon strength reduction factors are discussed. Strength reduction factors determined in this study are compared to published values. Compression strength data is normalized with 50% relative humidity compression strength as a baseline. This is done because a large variety of boxes are used, and this normalization allows statistical analysis across all of the box sets. Loss in compression strength is considered as a function of percent moisture content and relative humidity separately to evaluate the difference between the two.

4.1 Box Failure Mode Observations

As part of this project, the failure mode was recorded. The failure mode was either vertical panels bowing outward or inward. Typically, boxes with products inside cannot fail by the panels of the box bowing inward. Thus, bowing inward was only observed when testing empty boxes. Figure 4.1 depicts a graph indicating the breakdown of failure mode for all the boxes tested. Slightly over 28% of the boxes failed by having a box panel or panels bow inward. The remaining 72% of boxes failed by a panel or panels bowing outward.

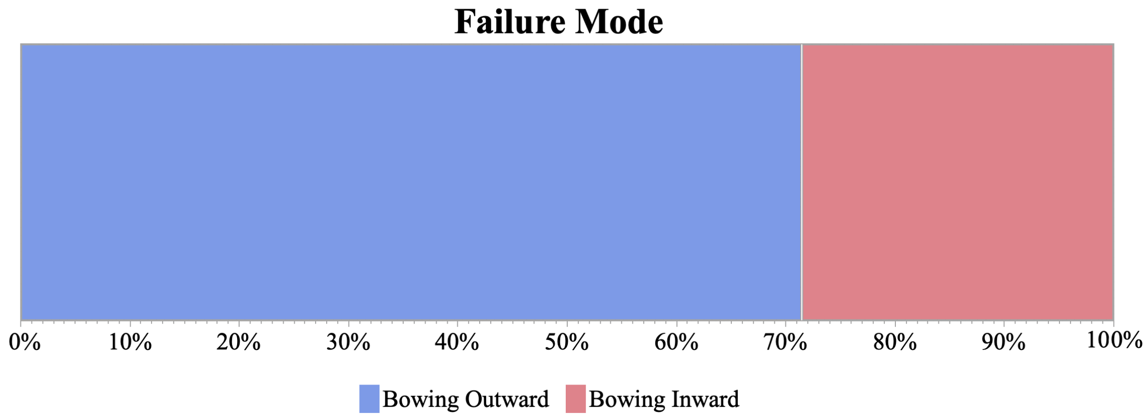

Figure 4.1: Box failure mode observations.

4.2 Repeat Batch Comparison

Three of the selected relative humidity levels were repeated twice to explore the testing repeatability. This accounted for six of the ten batches tested. The replicate relative humidities were 40, 60, and 80 percent relative humidity. A Least Squares Means Tukey's Pairwise Comparison test was used to compare the different populations and to identify statistically different populations (Ott, 2010). All data points, including outliers, are used for this comparison. This fit model compared box sets in each batch to the corresponding box set in the repeat test for comparison. Table 4.1 contains the results of the analysis. As observed in Tab. 4.1, the different levels that are connected by the same letter are statistically similar, whereas levels not connected by the same letter are different. This demonstrates that the 40, 60, and 80 percent relative humidity batches are similar to their specific repeat batches. Furthermore, the batches tested at relative humidity levels 40%, 60%, and 80% are statistically different from each other. Each of the repeat tests are statistically similar to the original test with a 95% confidence interval. Overall the results of the Tukey pairwise comparison demonstrate that the data is reliable.

Table 4.1: Tukey's Pairwise Comparison Between Repeat Batches

Tukey's Pairwise Comparison				
Level				**Least Square Mean**
40% RH	A			830.79
40% RH Repeat	A			817.66
60% RH		B		721.58
60% RH Repeat		B		730.31
80% RH			C	558.74
80% RH Repeat			C	549.32
Levels not connected by the same letter are significantly different.				

α=0.050

4.3 Percent Moisture Content vs. Relative Humidity

The relationship between the moisture content of the corrugated box and the relative humidity of the conditioning environment is plotted in Fig. 4.2. During testing, each set of ten boxes had three samples removed, which were then tested with the moisture balance to determine moisture content. The error bars indicate one standard deviation in the moisture content from the mean. As relative humidity increases, there is an increase in moisture content within the corrugated box. However, the relationship is non-linear and best fit by a quadratic equation Eq. (4), with an R-squared value of 0.972,

$$M = 0.00187{R_H}^2 - 0.108R_H + 8.30, \qquad \text{Eq. (4)}$$

where M is the moisture percentage and R_H is the relative humidity. A typical Kraft corrugated box in this study contain an average of 6.7% moisture when in equilibrium with a 30% relative humidity environment. On the other end of the range, a relative humidity of 90% results in an average of 13.7% moisture content in the box.

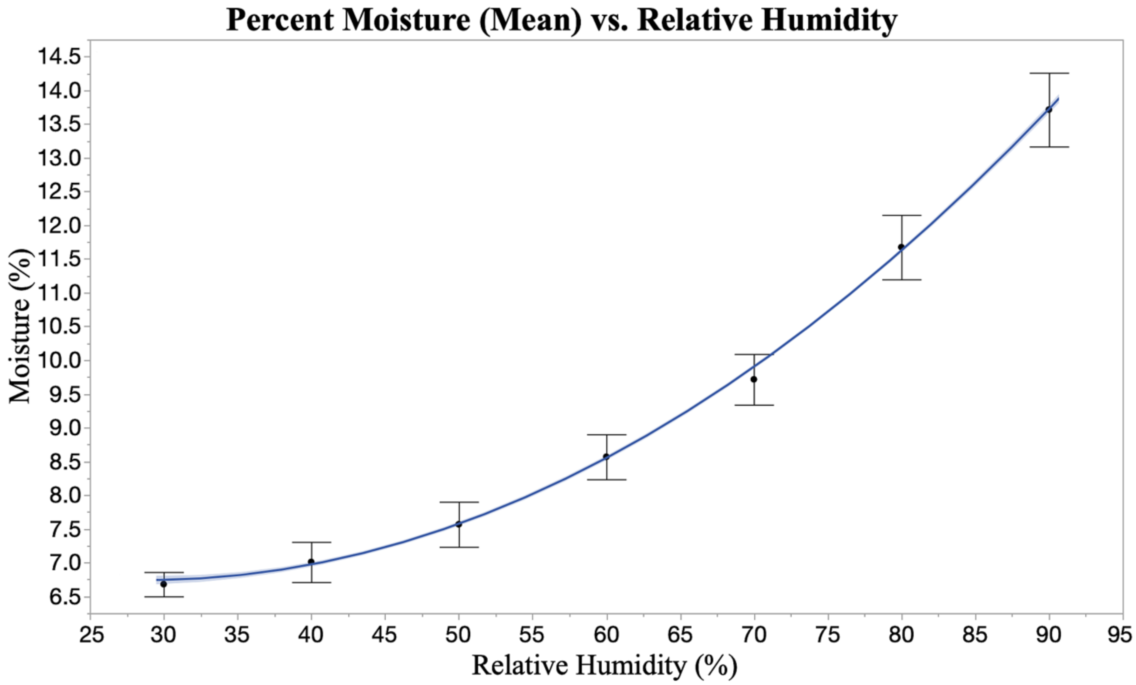

Figure 4.2: Mean Percent Moisture Content within Corrugated Board versus Relative Humidity.

From this study, a one percent increase in moisture content is observed within the corrugated board on average as relative humidity rises from 30% to 50%, whereas from 50% to 70%, a two percent change occurs. In contrast, a substantial 4 percent increase occurs, from 70% to 90% relative humidity.

4.4 Relative Humidity & Moisture Content Effect upon Strength Reduction Factors

Normalization of Data

Normalization was necessary due to the fact that each batch included 30 box sets that contained boxes where dimensional sizes, flute sizes, liner/flute caliper, box manufacturers, and recycled content varied. Specifically, normalization was applied to the compression strength of each box tested at each relative humidity. The following normalization was used,

$$\frac{CS_x}{\overline{CS}_{50\%}}, \qquad \text{Eq. (5)}$$

where CS_x represents the compression strength of an individual box set at a given relative humidity, x, and $\overline{CS}_{50\%}$ is the mean compression strength of the same box conditioned to 50% relative humidity. This normalization enabled statistical analysis across all 30 box sets at a given relative humidity and was applied to the data for each of the ten conditions considered, Tab. 4.3. For this study, the term "normalized compression strength" and "strength reduction factor" are used synonymously.

Outlier Treatment

An outlier is a point that is statistically outside a defined range and has the potential to skew the average (Ott, 2010). Within this study, outliers were identified by using the interquartile range method (IQR), Table 4.2. It was determined that there were 95 mild outliers and 18 extreme outliers out of 3,000 data points collected, and together they accounted for 3.8 percent of all boxes tested. Remaining data analysis was performed with outliers removed.

Table 4.2: Equations used for outlier identification

Fence	Formula	Outlier
Lower Outer	Q1 - 3(IQR)	Below = Extreme
Lower Inner	Q1 - 1.5(IQR)	Below = Mild
Upper Inner	Q3 + 1.5(IQR)	Above = Mild
Upper Outer	Q3 + 3(IQR)	Above = Extreme

4.4.1 Strength Reduction Factor and Relative Humidity

The normalized data of each batch was plotted against relative humidity, Fig. 4.3. It is evident that, as relative humidity rises from 30% to 90% relative humidity, box compression strength decreases at a non-linear rate. Error bars represent one standard deviation from the mean of the approximately 300 boxes tested at each relative humidity. A quadratic polynomial, Eq. (6), fit the variation in compression strength with relative humidity with an R-squared value of 0.806,

$$C = -0.00013{R_H}^2 + 0.0070R_H + 0.98, \quad \text{Eq. (6)}$$

where C is compression strength and R_H is relative humidity.

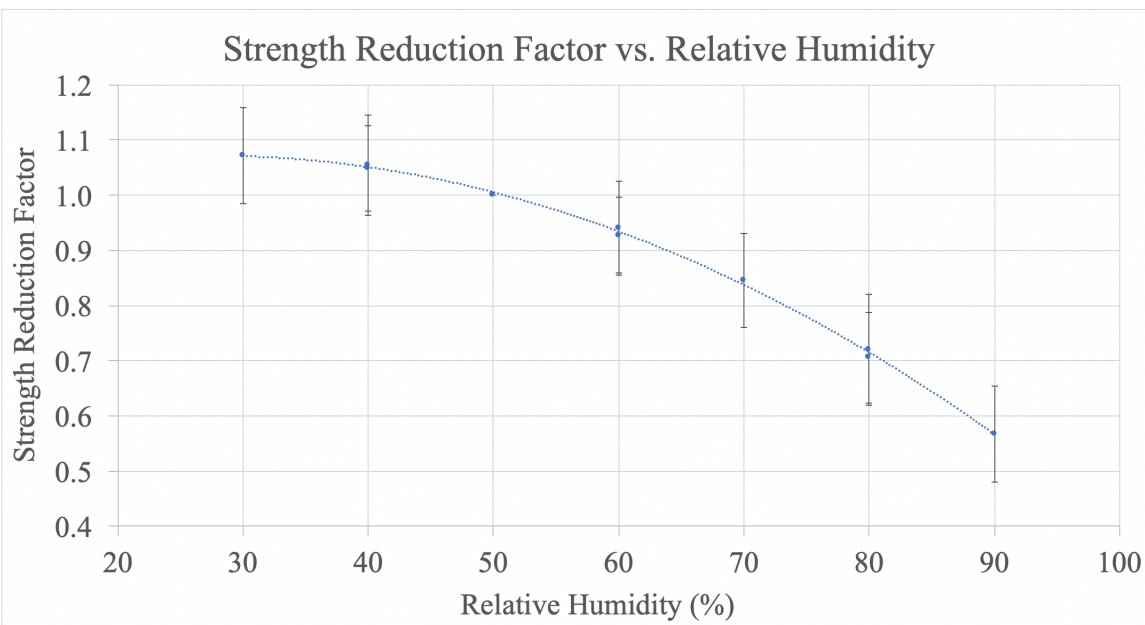

Figure 4.3: Strength Reduction Factor vs. Relative Humidity

4.4.2 Strength Reduction Factor and Percent Moisture Content

The normalized data of each batch was considered as a function of the measured moisture content, Fig. 4.4. All error bars in Fig. 4.4 indicate one standard deviation from the mean. The relationship between the strength reduction factor and moisture content is captured with a line fit between 6.6 - 13.7 % moisture content. The least squares fit yields,

$$C = -0.070M_C + 1.53 \qquad \text{Eq. (7)}$$

where C is compression strength, M_C is moisture content, and the R-squared value is 0.771.

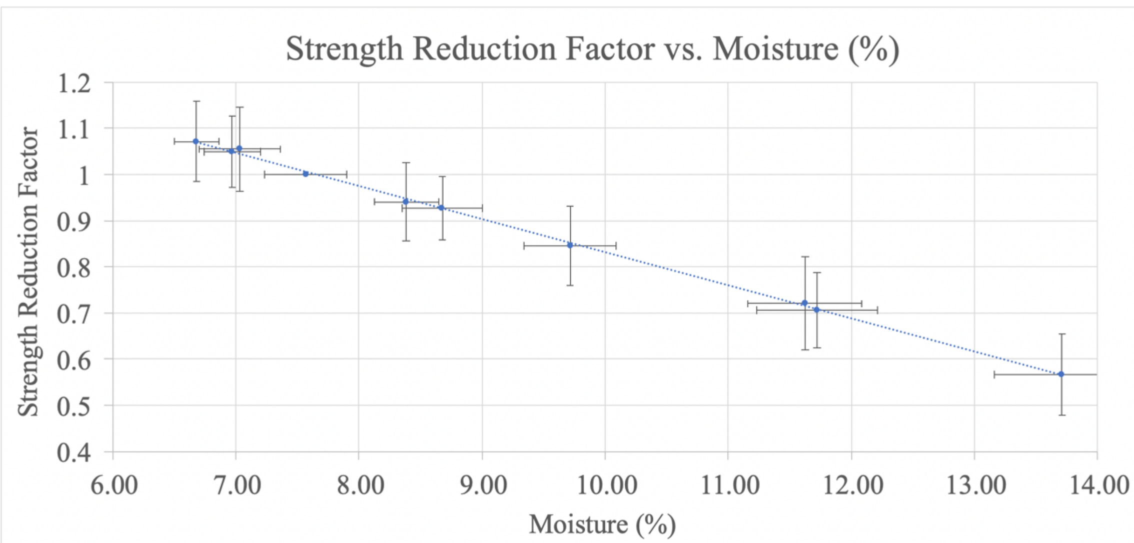

Figure 4.4: A plot of Strength Reduction Factor vs. Percent Moisture in which error bars indicate one standard deviation from the mean.

As observed in Fig. 4.4, the trend is such that for every 1% increase in moisture content, a 7% decrease in compression strength is observed. These results closely match the findings of Fellers and Bränge. They identified an 8% decrease in compression strength for every 1% rise in moisture content (1985). The data points plotted in Fig. 4.4 are listed in Tab. 4.3 for clarity.

Table 4.3: Normalized Compression Strength vs Percent Moisture

RH* (%)	Percent Moisture		Normalized Compression Strength (lb) *(Strength Reduction Factors)*	
	Mean:	**St Dev:**	**Mean:**	**St Dev:**
30	6.68	0.18	1.07	0.09
40	6.97	0.23	1.05	0.08
40	7.03	0.33	1.05	0.09
50	7.57	0.33	1.00	0.00
60	8.68	0.32	0.93	0.07
60	8.39	0.26	0.94	0.09
70	9.72	0.37	0.85	0.09
80	11.62	0.46	0.72	0.10
80	11.72	0.49	0.71	0.08
90	13.71	0.55	0.57	0.09

* *RH value is for reference only*

4.5 Strength Reduction Factors Comparison to Published Data

For comparison, the data from this study was plotted with the strength reduction factors from the four previous studies by Marcondes (1994), Maltenfort (1988), Hanlon et al. (1998), and the Fiber Box Association (2015), Fig. 4.5. Where necessary, factors were adjusted so that 50% RH is the baseline to enable comparison. Error bars indicating one standard deviation, was applied to the data from this study (Brown). Maltenfort and Hanlon's reported baseline values are slightly higher than the Brown data, whereas the FBA values are consistently lower than the Brown data. However, values reported by Maltenfort, Hanlon et al., and the Fibre Box Association are within one standard deviation of the values determined in this study. The Fibre Box Association's strength reduction value at 90% relative humidity varied slightly from the data in this study. It was just within one standard deviation of the Brown data at 0.48. The values reported by Marcondes are below of one standard deviation of the values in this study for all conditions reported.

Equation (6) was used to calculate a strength reduction factor for 75% and 85% relative humidity based on this study to make a comparison to Hanlon et al. and Maltenfort data at those reported. Since these are only estimates, no standard deviations could be calculated. However, the estimated mean of the standard deviations from the conditions tested was applied to the predicted strength reduction factor at 75% and 85% relative humidity, enabling comparison to the Hanlon et al. and Maltenfort data. The strength reduction factors of both Hanlon et al. and Maltenfort are within one standard deviation of the Brown data.

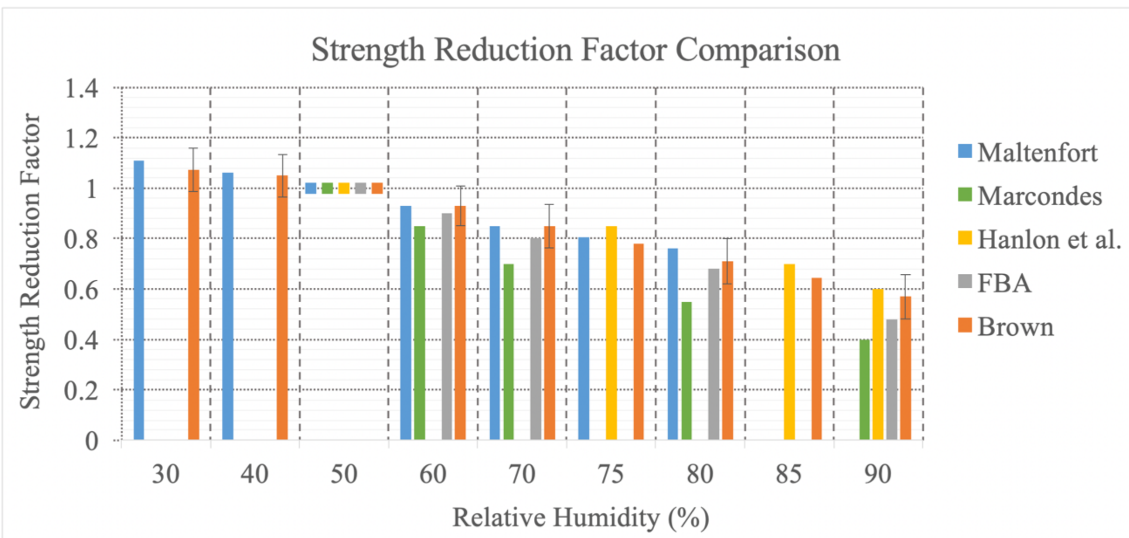

Figure 4.5: Strength reduction factors comparison between authors.

4.6 Brown Model Comparison to Kellicutt & Landt Model

Kellicutt and Landt's original 1951 study, which correlates loss in compression strength to percent moisture content for corrugated boxes, was compared to the moisture content model generated from this study, (Brown model). Kellicutt & Landt plotted results from four different lots of A and B-flute boxes on a semi-log graph, Fig. 2.9. The authors then fit an average between these lots and took the slope of the average to develop their model, Eq. (1). The Kellicutt & Landt model was based on a zero-moisture content box with a compression strength of 686 kg (1,516 lb.). Therefore, to enable comparison of the Kellicutt & Landt model to the Brown model, both models were used to predict the compression performance of a box with a moisture content ranging from 6.6 - 13.7%. From this study, 50% relative humidity resulted in a moisture content of 7.57%. This value was used with the Kellicutt & Landt model, Eq. (1), resulting in a box with an estimated compression strength of 406.9 kg (897.1 lb). This was the reference point between the two models and was used to calculate the Brown model, Eq. (7) estimates. Subsequently, the Kellicutt & Landt model, Eq. (1) and the Brown model were used to predict the compression performance of a box at different moisture content levels ranging from 6.6% - 13.7% and were plotted in Fig 4.6. Least squares fit trend lines are fit to the Kellicutt & Landt model predictions, Eq. (8) and the Brown model predictions, Eq. (9).

$$C = -52.8M_C + 1298, \qquad \text{Eq. (8)}$$

$$C = -62.8M_C + 1372, \qquad \text{Eq. (9)}$$

where C is compression strength and M_C is moisture content. Error bars associated with the Brown model represent one standard deviation from the mean. Note that the slopes and y-intercepts of the two plotted models are not the same. This is due to the fact that Kellicutt & Landt's model is not linear, and estimated from a semi-log plot. The Brown model exhibits a slightly steeper slope and a greater predicted compression strength at a moisture content of zero than the Kellicutt & Landt model. The percent difference between the two models was plotted in Fig. 4.7. The model agreement is within 2% from 6.6 – 9.8%

moisture content. However, the predicted compression strength of the box using the two models varies significantly above 9.8% moisture content, reaching a maximum of 15.8% difference at 13.7% moisture content.

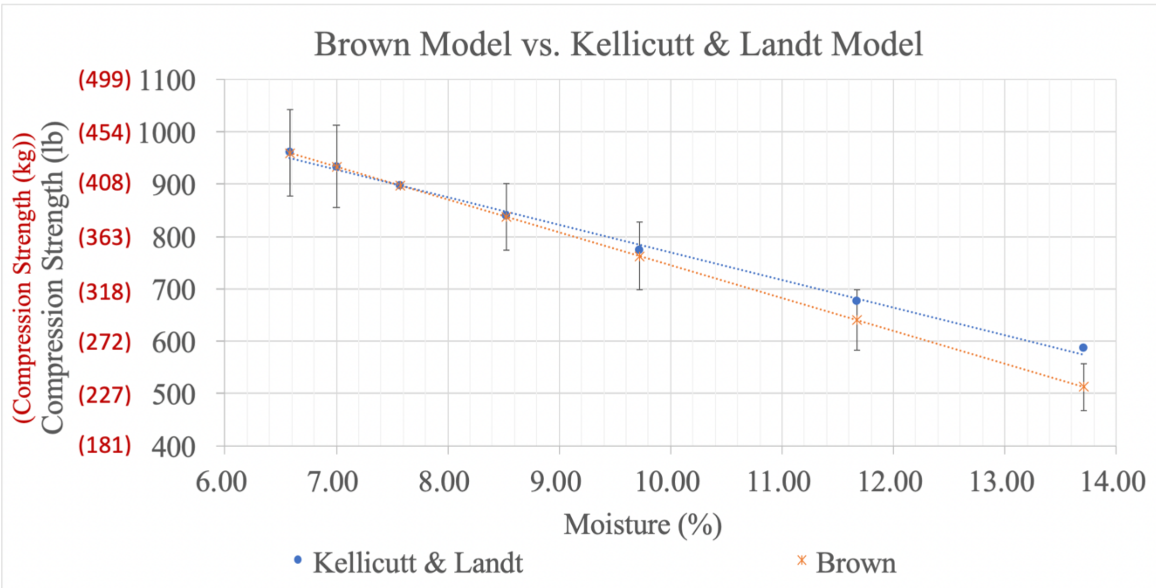

Figure 4.6: Brown and Kellicutt & Landt model estimates of box compression strength as a function of box board moisture.

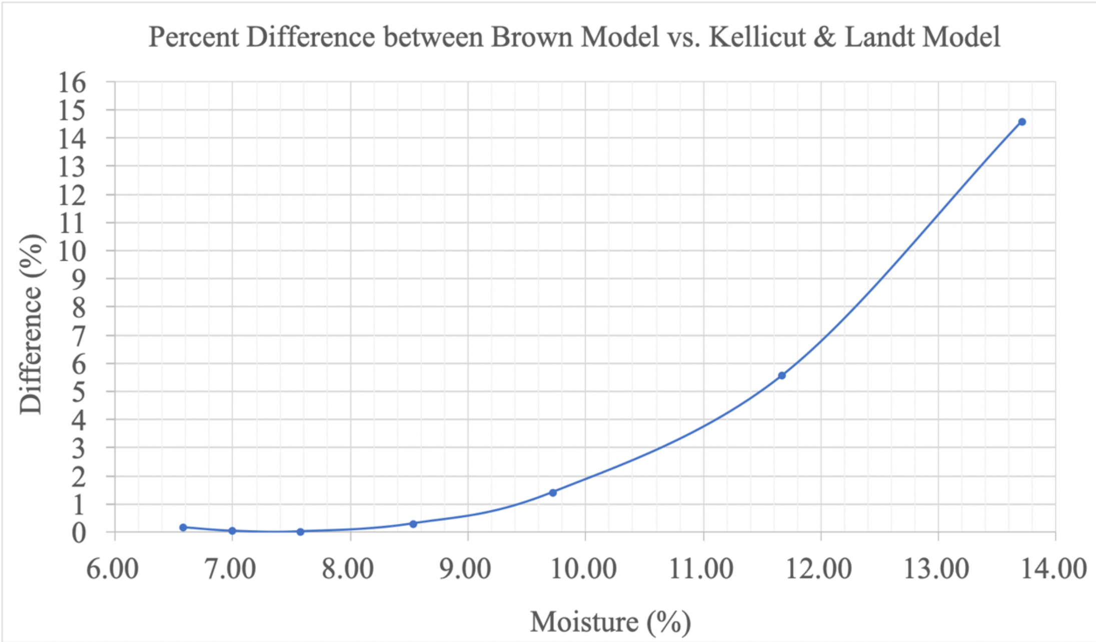

Figure 4.7: Percent difference calculated between Brown and Kellicut & Landt models.

CHAPTER FIVE

CONCLUSION

The corrugated box industry, through the organization of the FBA, supplied a representative assortment of Kraft corrugated boxes for this study. These specimens were preconditioned for a minimum of 48 hours, at 35ºC (95ºF) and 30% relative humidity and then were moved to a conditioning chamber and conditioned for a minimum of 72 hours at the desired conditions. The specimens were then compression tested to failure in the conditioning chamber, yielding total compressive load versus deformation data. Following compression testing, the moisture content of three out of every ten specimens were measured using a loss-upon-drying moisture balance. In total, 3,000 boxes were compression tested, and 900 moisture balance samples were tested for this study.

Two separate batches of boxes were tested separately at previously tested relative humidity levels; 40, 60, and 80 percent relative humidity to quantify testing repeatability in this study. Tukey's pairwise comparison was used for analysis, which compares differences in population means. From this analysis, it is concluded that the box compression performance between the repeat batches was statistically similar at the same relative humidity level and statistically different between the three humidity levels.

The relationship between relative humidity and moisture content for typical corrugated boxes suggests that, as relative humidity rises above 30%, a non-linear increase in moisture content was observed. Furthermore, this relationship was best captured by a second-order polynomial equation with an R-squared value of 0.972.

The relationship between average compression strength and moisture content of corrugated boxes was linear from 30% to 90% relative humidity and has an R-squared value of 0.771. The relationship between average compression strength and relative humidity was best captured by a second-order polynomial equation with an R-squared value of 0.806.

Strength reduction factors were computed and compared to those reported in previous studies. The strength reduction factors calculated in this study were in general agreement with previous studies with a couple of exceptions. The strength reduction factors reported by Hanlon et al. (1998) and Maltenfort (1988) were slightly higher than those of this study, but they were well within one standard deviation of the mean. The FBA (2015) strength reduction factors were all well within one standard deviation of the mean except for the value at 90% relative humidity. The FBA strength reduction factor at 90% relative humidity was exactly at one standard deviation from the mean in this study. All of the strength reduction factors reported by Marcondes (1994) were well below one standard deviation of the mean determined in this study. Overall the strength reduction factors resulting from this study are recommended over those of previous studies because the methods and procedures of the experiment are fully disclosed and the large sample size of boxes tested (3,000).

Lastly, Kellicutt & Landt's 1951 model that correlates loss in compression strength to percent moisture content for corrugated boxes was compared to the model developed in this study. A least squares fit was plotted to each model and the slopes vary by 19%. The difference between models over the ranges studied was no greater than 16%. The variation of slope resulted in a maximum variation in box compression strength of 16% at 90% relative humidity.

APPENDIX

Measuring and Correcting Parallelism for Compression Testing

It was important that the platens of the fixed platen compression system, remain parallel throughout testing. For this reason, TAPPI Standard T804 *Compression Test of Fiberboard Shipping Containers* limits the tolerance for the two platens to 1 mm (0.04 in.) per 305 mm (1 ft.) in length and width (TAPPI T804, 2012). A dial indicator made by Mitutoyo (Kanagawa, Japan, US Office: Aurora, IL), Model: ID-S1012EX, was used to measure the parallelism of the platens of the compression system used in this study, Lansmont Squeezer (Monterey, CA). The dial indicator was attached to a magnetic base, Fig. A-1, which was sequentially set at all four corners to record the parallelism of the platens. The dial caliper was mounted to a magnetic base and placed between the two platens at the four corners, starting with the right front. It was then moved to the next three corners, left front, left rear, right rear, and measurements were taken and analyzed with the right front as a zero position (datum). The parallelism measurements were taken once daily before testing began. It was not repeated throughout the day to verify consistency. In Tab. A-1, all red and bold measurements are out of specification of TAPPI T804.

Throughout the project, a better method was devised in order to reset the parallelism without the danger of damaging the load cell. First, manually setting the Lansmont Squeezer top platen, so that it is almost touching the bottom platen, then with the limit set to 453.6 kg (1,000 lb.). Next, press run and allow the Squeezer to complete a testing cycle. The squeezer then gradually completes a cycle until it reaches 453.6 kg (1,000 lb.) and automatically stops. This method was used beginning with the 60% relative humidity repeat batch, on July 7, 2018 and continued until the project came to a conclusion. The green highlighted region of Tab. A-1 contains the results of this new method of resetting the parallelism.

Figure A-1: Dial indicator and base.

Table A-1. Platen Parallelism Recordings.

Date	Relative Humidity	Right Front	Right Rear	Left Front	Left Rear
3/13/18	60%	0.000	0.039	-0.013	**-0.052**
3/14/18	60%	0.000	0.031	-0.015	**-0.046**
3/16/18	60%	0.000	0.029	-0.016	**-0.044**
3/18/18	60%	0.000	0.029	-0.016	**-0.044**
4/4/18	40%	0.000	0.027	**-0.044**	**-0.045**
4/6/18	40%	0.000	0.029	-0.016	**-0.045**
4/9/18	40%	0.000	0.036	-0.015	**-0.051**
4/11/18	40%	0.000	0.033	-0.015	**-0.049**
4/13/18	40%	0.000	0.031	-0.015	**-0.047**
5/10/18	50%	0.000	0.031	-0.012	**-0.045**
5/11/18	50%	0.000	0.036	-0.013	**-0.050**
5/13/18	50%	0.000	0.038	-0.013	**-0.052**
5/15/18	50%	0.000	0.038	-0.013	**-0.051**
5/18/18	50%	0.000	0.032	-0.014	**-0.047**
5/23/18	70%	0.000	0.037	-0.011	**-0.052**
5/24/18	70%	0.000	0.009	-0.022	-0.023
5/25/18	70%	0.000	0.018	-0.025	-0.006
6/1/18	70%	0.000	0.013	-0.024	-0.010
6/6/18	40% Repeat	0.000	0.014	-0.025	-0.009
6/7/18	40% Repeat	0.000	0.017	-0.026	-0.007
6/8/18	40% Repeat	0.000	0.024	-0.028	-0.002
6/11/18	40% Repeat	0.000	0.027	-0.029	0.000

Table A-1. (Cont.) Platen Parallelism Recordings.

Date	Relative Humidity	Right Front	Right Rear	Left Front	Left Rear
6/20/20	80%	0.000	0.016	-0.026	-0.009
6/24/18	80%	0.000	0.017	-0.025	-0.007
6/26/18	80%	0.000	0.019	-0.026	-0.015
6/27/18	80%	0.000	0.013	-0.025	-0.010
6/28/18	80%	0.000	0.010	-0.024	-0.012
7/18/18	60% Repeat	0.000	0.009	-0.023	-0.012
7/19/18	60% Repeat	0.000	0.012	-0.024	-0.011
7/20/18	60% Repeat	0.000	0.013	-0.024	-0.010
7/23/18	60% Repeat	0.000	0.014	-0.025	-0.010
8/1/18	80% Repeat	0.000	0.018	-0.026	-0.006
8/2/18	80% Repeat	0.000	0.014	-0.024	-0.009
8/3/18	80% Repeat	0.000	0.012	-0.024	-0.010
8/6/18	80% Repeat	0.000	0.012	-0.024	-0.010
8/15/18	90%	0.000	0.014	-0.024	-0.009
8/16/18	90%	0.000	0.013	-0.024	-0.009
8/17/18	90%	0.000	0.014	-0.024	-0.009
8/20/18	90%	0.000	0.012	-0.021	-0.008
8/21/18	90%	0.000	0.009	-0.020	-0.010
8/22/18	90%	0.000	0.012	-0.020	-0.007
12/12/18	30%	0.000	0.021	-0.016	0.003
12/13/18	30%	0.000	0.014	-0.020	-0.005
12/14/18	30%	0.000	0.016	-0.021	-0.004
12/17/18	30%	0.000	0.014	-0.020	-0.005

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