Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Process Evaluation and Performance Enhancement of Corrugated Board Fabrication.

(A case of Burayu Packaging and Printing Industry)

A Thesis Submitted to the Graduate School of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Mechanical Engineering (Manufacturing Engineering)

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DECLARATION

Addis Ababa University

School of Graduate Studies

This is to certify that this thesis prepared by **Yohannes Eshete**, entitled: **Process Evaluation and Performance Enhancement of Corrugated Board Fabrication,** do hereby declare my original work with the help of my advisor, and that it complies with the requirements of the university and meets the established standards regarding originality and quality, and that it has not already been submitted in whole or in part for a degree at any university or institution.

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NOMENCLATURE and ABBREVIATIONS

AAIT: Addis Ababa Institute of Technology

BCT: Box Compression Test

CD: Cross Direction

CFB: Corrugated Fiber Board

ECT: Edge Compression Test

FM: Fluting medium

FEFCO: Federation European Fabricants Carton Ondule.

MBP: McKee Box Prediction

PAT: Pin Adhesive Test

RCT: Ring crush test

REF: Reference

RS: Reel Size

TL: Test liner

ZD: Thickness direction

Symbols

CBFS: Corrugated board fabrication speed [m/min]

CL: Thickness of the linerboard [mm]

Cm: centimeter[cm]

Gsm: paper grammage [gm /m^2]

H: Calliper of the corrugated paperboard [mm]

N: Newton

Z: Package perimeter [m]

ABSTRACT

The materials utilized, the conversion process, and other factors could all have an impact on the corrugated board performance. The objective of the thesis to quantify the mechanical strength of the corrugated board, the adhesive strength, the paper compression strength at fabrication process of investigated the pin adhesive, edge crush, box compression strength and material properties test at standardize methods. Based on the experimental result the reel size of **165,185,205,220 cm** at fabrication speed on **50,65,80,95 m/min** which can be used to determine varies result of compression strength exhibited at 50 m/min, and the fabricated board was the maximum, **pin adhesive 356,352,351,349 Newton**, **edge crush 4.5,4.3,4.2,4.4 KN/m**, **pure box compression 112- 114 kg strength** were shown. Reel size 220 cm fabricated at 80 m/min refers to the laboratory results minimum strength were performed. The **Maltenfort model** by correlating the measured **ring crush test** with the theoretical edge compression test enable to know the board strength of how much the variables degraded the strength of the combined board as of reel size 185,205,220 cm at 80 and 95 m/min during the process. The **regression equation** which can be used to evaluate the linear effect of the process and can be used to predict the performance of the box and enable it to enter into optimum fabricating process as well as strength improvement decisions. Boards will have better strength if they follow optimum process can be achieved by balancing and selecting the variables of fabricating speed, reel size, and material properties which helps to identify the strength of the board and evaluate the fabrication process. Overall, this study provided experimental and **McKee box prediction** are done for the evidence of structural performance and delamination strength of the corrugated fiber board by aligning a process through runnability.

Keywords: Pin adhesive strength, corrugated board compression strength, Defect Analysis of corrugated board, paper compression strength.

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CHAPTER ONE

INTRODUCTION

1.1 Back Ground of the Study

Corrugated Fiber board packaging are extensively used in the packaging of industrial as well as consumer goods. Packaging becomes very important because the packaging products and environmentally friendly and at the same time it is recycling. In the industrial production, the demand for corrugated paper boxes increasing every year [1]. These boxes have got distinct advantages such as light in weight, easy to fabricate, Strength, Versatility, and Recyclability. Before considering factors that either limit or contribute to paper's strength, it is important to consider the widely different physical requirements of different types of paper at the increased usage of recycled fibers in corrugated boxes, it has become necessary to study the properties of test liners, medium, and the combined board made recycled fiber under constant relative humidity and temperature the greatest loss in strength during tested, at the edgewise compressive strength [2].

A further result of the study was that recycling causes a decline of up to 25 % in top to bottom compressive strength of container after one cycle. At the of effect resulting from the corrugated board manufacturing process which is the Wash boarding depth and it is linearly related to the amount of glue applied and formed by the shrinkage of the glue in between of the liner and the fluting of the corrugated board during drying. The wash boarding depth and paper grammage strongly correlated at the Edge crush test (ECT) performance [3]. And another problem during fabrication process is the High/low flutes refer to height variations in the fluting web after the corrugation. It has a negative effect on the corrugated board strength properties and may cause uneven bonding typically high/low flutes is a cause of mechanical issue [4] ,[5].

In addition to this fractured problem faced in the corrugation process and also the formation of the corrugator bond is affected by the properties of the paper and adhesive, and by the corrugator process variables of heat, moisture, pressure, and speed. The flute fracture of runnability of the fluting medium determines the operation speed during the production of a single-faced corrugated paperboard. High tension on the fluting medium between the top and bottom tips of the corrugating rollers inside the single facer causes flute fracture. This is further demonstrated by the fracture of the flanks of the fluting medium and the fracture of the flute tips at high bending stress that exceeds the tolerable limit [5] [11].

The paper passes through the roller, there will be various pressures, which will negatively affect the production process. When exposed to heat, the materials have different mechanical properties, such as fracture, compression, delamination, and so on during converting operation. To predict the strength of a material is one of the most challenging problems facing. Considerable progress has been made toward predicting the behavior of materials, while failure properties are much more intractable as well as being largely empirical. Paper is a complex material and understanding its behavior at a fundamental level is a formidable task; nevertheless, there is a substantial body of knowledge which contributes to the understanding of the ultimate strength of paper in terms of its dependence on raw materials and papermaking process variables [6].

Factors that may have an impact on the board's success over the course of its existence and the quality is determined by the choice of materials, including the kind of paper, flute size, and adhesion type. These parameters were demonstrated to have a substantial influence on the corrugated board's characteristics, particularly in terms of its mechanical strength [7].The Combination of paper that made up the corrugated fiberboard is crucial since both liners and flutes will have their own specific target. Damage to the corrugated fiber board during production is another possibility. If moisture and temperature are not properly regulated during the first step of the process, the paper's characteristics could be greatly impacted [8].

1.2 Statement of the Problem

The potential products of the case company are mainly fabricated by C-Flute, B-Flute- and E -Flute board and subsequently different packaging products are used for soap, pasta, edible oil and biscuit. The main and major once is according to the customer complaint issue are, Strength, and delamination, regarding to this the thesis are focused on the primarily study of how to enhance the strength and minimizing the delamination of the board thorough fabricating process. In addition to the unpredictability of the paper properties during the converting process, damage will weaken the mechanical properties of the board and allows failure to propagate quickly from the localized failure area on the board [9] . During high speed, the corrugated board to be delaminated at the same time at low speed the board become cracking .This situation reduces the overall strength of the board, during the fabrication of corrugated fiber board, various mechanical processes go through, and this problem is mainly paper, it is important to know the properties of the paper and it is vital to study the qualities that the corrugated board acquires after converting in order to get the corrugated fiber board properties that are suited for particular applications [10]. At the same time take into account the vastly varying physical properties of paper and the conversion process before evaluating elements that either restrict or add to paper's strength. Hence the knowledge of manufacturing the corrugated fiber board and the types of raw materials can be a great help in minimizing the problems [11]. So, it the test liners and fluting Paper has different properties and mechanical characteristics, during converting process and it can be adapted to grow strong and strong through process [12] [13].

Due to this reason the variables are suitable as showing the strength obtained by linking it to the fabricated speed, reel size, box dimension and not only from the point of view of being able to know the different mechanical performance of the board, but also to adjust or reduce the possible source of failure according to the results obtained and the aforementioned problem.

1.3 Objectives of the Thesis

1.3.1 General Objective of the Study

The general objective of the thesis is to identify and determine the performance of the board strength at the reel size of 165,185,205, 220 cm on the fabrication speed of 50,65,80 and 95 m/min and evaluate the fabrication process of the corrugated fiber board at linear regression equation.

1.3.2 Specific Objectives of the Study

- RS 165, 185, 205 and 220 cm at the fabrication speed of 50, 65, 80 and 90 m/min of the board to show the strength of the glue adhesive and the delamination characteristic of the corrugated fiber board.
- To show and compare the compression strength of the test liners and fluting paper (paper property) with the combined board strength of RS 165,185,205,220 cm.
- Perform box strength prediction using the McKee and the compression strength of the fabricated board of RS165, 185, 205, 220 cm at 50, 65, 80 and 95 m/min, and evaluate the performance of the actual box compression and failure behavior of ECT.

- Describe and analyzing the relationship of paper strength (RCT) with gram/m^2, PAT with ECT on RS 165, 185, 205 and 220 cm at 50 and 80 m/min, paper and board caliper with paper, board compression strength board by linear regression equation.

1.4 Scope of the Study

Corrugated Paper packaging are extensively used in the packaging of industrial for consumer goods and becomes very important because the products light in weight and environmentally friendly at the same time it is recycling. The paper has different mechanical properties of during converting process. In the thesis, mainly used during converting to determine their role in board strength and failure, for which PAT, ECT and BCT was done using FFECO, ISO, Tappi method. Similarly, using RCT, the difference between theoretical and actual compression test from ECT has been observed in the converting board at the real size and speed variables. Also, by using the compression test result and box geometry, board caliper the theoretical McKee box compression strength was made to determine the top box compression strength and so the board stiffness test not considered and Physical properties such as tensile strength, burst strength, paper stiffness, tearing test and flat crush, flexural bending test, effect of moisture and temperature have not been explored during the fabricated of combined corrugated board.

1.5 Significance of the Study

The strength techniques bring tangible changes in the fabricated process of corrugated board. The thesis can provide significant contributions to different users especially the packaging industry and will be used as baseline information for contemporary researchers in similar areas. As a result, the research enlists the major defect analysis faced by the board fabricating sectors and recommends possible solutions and the way of enhancing the strength performance of fabricating board in infighting process operation with variables.

1) Determine the intensity and nominating the mechanical performances of the box on the finding result.
2) To ensure that the most important board property would be given the steering specification level compared with the rest of the specified properties.
3) Enable to know in detail about how to perform the manufacturing processes as per the respective variables and appropriate way of process operation.

4) Encourage existing and new corrugated paper box manufacturing factories to fabricate enough quality board strength, so as to minimizing defects and enable it enhancing the performance of the corrugated board.
5) Encouraging the Corrugated box manufacturers able to determine the extent of the process operation and variables has an effect of the strength of corrugated fiber board.

1.6 Research Question

The thesis is expected to answer the following question:

- What is the effect of compression board strength during the fabrication of the board at different speed, reel size and which has the maximum strength of the tested board?
- What is the effect of glue strength and how to analyze the delamination of the board at speed, reel size, adhesive and paper properties?
- Is the paper substate strength and its relationship at the compression strength of the combined board at the aforementioned variables are applicable for conversion process?
- How to discover ways of improving the mechanical strength at converting process, and evaluate their relationship between PAT, ECT and paper properties?

1.7 Limitation of the Study

When dead weight is applied to the box, it is difficult to see the small fracture on the inner and outer parts of the box, which has limitations in determining the actual bearing capacity with accuracy. It is made by connecting the strength of the board to the experimented sample made using the simple McKee formula and box geometry. Similarly, the customer's different board size the strength was measured using steel weights, which does not show the graphical display as well as the box failure behavior and reduces accuracy.

1.8 Organization of the Thesis

Chapter one: - this chapter indicates the background of the company and the study of including an introduction about the corrugated board and performance of the paper board. In addition, it describes the major and particular objectives of the investigation, problem justification, scope of the study, and limitation of the study.

Chapter two: - the literatures discuss, the manufacturing and properties of the corrugated board and relevant terminology.it also investigated the work done in characterizing and the performance properties of the corrugated board, process evaluation and runnability relationships of the paper board and geometrical profile.

Chapter three: - describes the materials, methods and experimental procedure that used for the fabrication of corrugated board and specimen preparations for performance testing were carry out the experiment of this thesis.

Chapter four: - explains the result and discussion of experimental technique in detail.

Chapter five: - gives a conclusion, suggestions, and directions for the thesis's future work in light of the research's findings.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Corrugated Paper boxes are extensively used in the packaging of industrial as well as consumer goods. In some of products like glass and cigarettes, pharmaceuticals, soaps & cosmetics, biscuits, hosiery, toys, spaghetti and macaroni. Packaging becomes very important because the packaging products and environmentally friendly and at the same time it is recycling[1].

In the industrial production, the demand for corrugated paper boxes increasing every year. These boxes have got distinct advantages such as light in weight, easy to fabricate, Strength, Versatility, and recyclability as Biancolini said [14]. The strength and effectiveness of a corrugated package are influenced by a variety of factors, including the quality of the input cellulose fiber, the mechanical properties of the individual parts and the combined board, the manufacturing process control protocol, machine precision, the human factor involved in the corrugation process, and other factors. By reducing the quantity of material used to create corrugated paperboard packages and directing the design of packages with higher performance qualities, knowledge of these crucial attributes will help improve the structural performance of the package [15].

2.2 The Manufacture of Corrugated Boxes

The first part of the corrugating machine is known as the single facer; since it is here that the medium is fluted and attached to the top liner, making single-face board. The operation can be divided into four basic sub-operations (1) the unwinding and conditioning of the two webs (2) the actual corrugating of the medium (3) combining and gluing the two webs and finally (4) holding the single face in the bridge to allow the glue to set or dry.

The drawing in figure 2.1 shows the medium being supplied from an unwind which is under the part of the machine known as the bridge. The top liner is unwound from a position at the outside of the machine. To heat them before combining steam may also be used especially on the medium to increase its flexibility. The web to be corrugated is passed between two rolls with corrugated surfaces or intermeshing teeth all across their surface which force the web into the fluted shape. Before the fluted medium and the adhesive leave the corrugating roll the top liner is pressed against the glued surfaces [16]. The adhesive is a starch solution of the proper solids webs together as they pass up to the bridge.

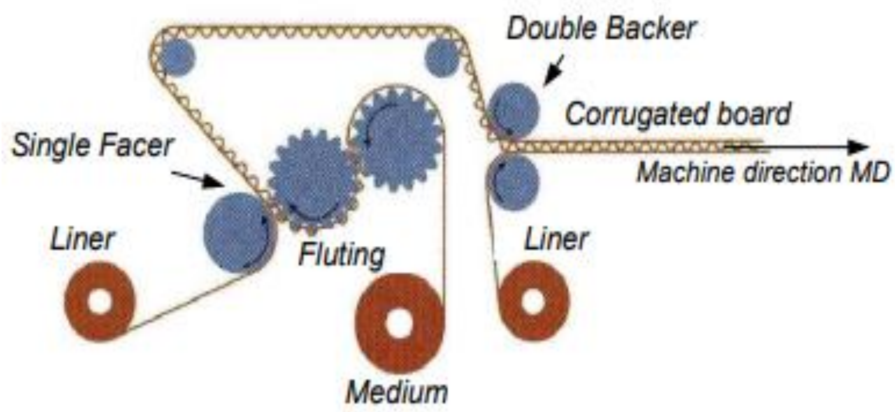


Figure 2. 1: Manufacture of corrugated board [15].

Double Backer, if double face board is to be made the single face produced by the operations just described must be glued to another liner. As can be seen in figure 2.1 the single face is brought from the bridge and adhesive applied to the tops of the exposed flutes are not crushed but that all flutes receive enough adhesive to bond the bard together [17].

The RSC box is the simplest and most economical box to manufacture. The main feature of this style of box design is that the box flaps meet in the center when folded. These boxes are normally manufactured in a single process on an in line flexographic printer Slitter Folder Gluer [18]. During these operations the corrugated board is subjected to large multi-axial stresses that can result in plastic deformation and localized damage. These effects can affect the corrugated board's mechanical properties.

2.3 Runnability Chartcerstics of the Corrugated Board

In order to understand the stress-strain behavior of a medium during corrugating, its physical characteristics and runnability were compared. The fastest permitted corrugating speed without flute fracture is known as runnability. Other variables that depend on speeds must be taken into consideration when analyzing the relationship between runnability and the stress-strain condition of the medium. It may be expected that the rate of stressing will grow as the corrugating speed is raised [19], [20]. Due to the medium's quicker passage through the corrugator, the medium's temperature will drop and its moisture content will rise. Changes in these environmental factors (caused by an increase in speed) are predicted to have the following effects on the induced stresses and strains: (a) an increase in transport tension due to increased friction and increased impact at the entrance of the labyrinth; and (b) a potential change (the direction of which is unknown at this time) in the distribution of strain between bending and shear. Taking into account the impact at the entry to the labyrinth also shows that the medium's fatigue behavior may be important for corrugating. The permitted strains that the medium can safely bear may also be predicted to decrease as the rate of stressing increases owing to speed increases, whereas allowable strains that are likely to increase due to changes in temperature and moisture [21] .

If the produced strains are greater than the medium's strength under the current conditions of heat, moisture, and rate of stressing, the medium fractures [22]. The medium has nearly reached its full flute shape at this time but has not yet been subjected to the enormous transverse compression that occurs at the center of the labyrinth and "completes" the molding. The medium is currently under transport, bending, shear, and transverse compression loads [23]. To identify the elements of the corrugating process that are crucial to runnability and to assess the type, distribution, and, if possible, estimate the size of the stress and strains in the medium during molding.

2.3.1 Web tension

One of the elements affecting runnability as it passes through the maze of the corrugating rolls is the quantity of web or the transport strain on the corrugating fluting medium. Unwanted speed at the labyrinth can result in defective or poor corrugation since there isn't enough time for the production of flutes and their adhesive pick-up. Moreover, the linerboards and the medium fluting may not bond well as a result, leading to delamination [24].Several researchers examined the faults that resulted from strain on the fluting medium between the corrugating sites, just before the single facer. To reduce the coefficient of friction that consequently minimizes the stress, lubrication can be applied to the surface of the fluting medium [25]. Further steps to lessen the tension on the fluting medium include regulating the speed of the pre-feeders and the roll stand's brakes. Moisture content and temperature were reported by the fluting medium should ideally have a high tensile strength and a low coefficient of friction in order to prevent flute fracture during the creation of flutes. In contrast to other flute profiles, A-flute fractured at a slower corrugator speed than B-flute, while B-flute shattered at a slower corrugator speed than C-flute [17].

It could be necessary to use a pre-feeder to maintain constant speed and tension in order to prevent the issue of fractures at the flute tips. Also, it might be necessary to adjust the pre-feeder and break tension on a regular basis to level out any piping in the paper and maintain constant tension throughout the flute nip line to prevent high-low flutes and creasing [26]. The stresses incurred during printing and converting of the board can stiff these layers and cause ply bond failure this failure can occur on printing presses, on gluing and folding lines or on filling machines.

2.3.2 Flute fracture

When the flutes are formed in the single-facer, the corrugating medium fiber network physically separates during the process, which is referred to as having "fractured flutes." Two potential separation kinds are described by the theory of material engineering. Forces acting in the medium's in-plane machine direction cause one type of separation, while a shear force acting in the medium's machine direction/thickness (caliper) direction causes the other [27]. Paper's in-plane failure types are typically brought on by a tensile or tear force and breakdown due to shear strain is frequently accompanied with bending force that results in delamination. The process of creating flutes involves both tensile and bending forces. It can appear that the medium only bends at the tips of the last flute, where the medium substance is placed [28].

2.3.3 Recycled paper

The biggest decrease in strength attributes happens when the first recycle; The liner board's inclusion of neutral sulfate semi-chemical fibers and recycling may both contribute to some of this reduction in strength [29]. Another finding of the study was that after one cycle of recycling, a container's top-to-bottom compressive strength can decrease by up to 25%. When virgin pulps were replaced with 100%, the box compressive strength and other attributes of combined board, linerboard, and corrugating medium were all lower [30]. This was discovered during an investigation into the furnish combinations to understand how they affect the recyclability of corrugated fiberboard. Properties including flat crush test, burst strength, and compressive strength are lost when recycled clean corrugated fiberboard is used and the percentage of regenerated fiber tends to increase these losses. Especially at recycle paper, the strength of the paper loss because of reducing the elastic module and tensile strength, due to temperature effect and the recycled paper drops tensile properties compare to virgin paper [31].

2. 4 Mechanical characterization of paper

Three known axes can be nominated in a paper sheet. The three known directions (machine direction = MD, cross direction = CD, thickness direction = ZD) in ordinary paper.

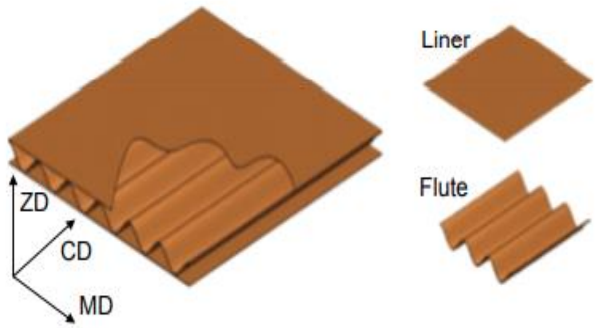


Figure 2. 2: Dimensions of corrugated paperboard panels [15]).

MD is the machine direction, CD the cross-machine direction and ZD the thickness direction. The Differences in CD and MD respect to the orientation of the fibers in the (the above figure) machine direction of the paperboard sheet complicates the creasability and foldability to maximize formability and end-use performance, corrugating medium needs to have the right combination of MD and CD qualities. High CD compressive strength is necessary for linerboard, but certain performance requirements also call for adequate MD qualities [15].

2.5 Quality chartcerstics & Defects evaluation for corrugated board

Performance of corrugated boards is constrained by a number of variables, some of which have a direct impact on board quality. For instance, corrugator productivity and the performance of corrugated board in its final application are both impacted by high-lows, flute fracture, bond quality, and board strength. All of the layers in the structure must be tightly bonded for the corrugated board to be manufactured. Additionally, the board must be sufficiently flat for processing and have sufficiently smooth surfaces for printing and that the variables to be optimum as well as to the functionality of the corrugated board performance. Different variable and processing parameter have effect of board quality characteristics is as follow: -

I.Warp

After cutting the board into sheets, non-uniform dimensional variations between liners result in warp. When feeding corrugated board to conversion machines, high warp creates issues. Uneven moisture balance-induced warp predominates in the cross direction [32]. The dominant fiber orientation is in the machine direction, which explains this. Because the fibers contract and expand in thickness considerably more so than in length, the corrugated board's resulting warp is in CD [33]. Up-warp is shown when the upper liner shrinks more as a result of drying, and vice versa when the lower liner shrinks more as a result of trying.

If changes in web tension and mechanical flaws are disregarded, it is believed that twist warp is brought on by a combination of different fiber orientations and moisture imbalances between liners. The orientation of liner fibers cannot be changed by corrugators; however, it has been demonstrated that the twist warp can be eliminated or reduced in the same way as the CD warp by altering liner moisture balances [34] .

II. Post Warp

The term "post warp" describes the warp that appears after the sheets of corrugated board have been stacked at the end of the corrugator line. The top and bottom liners' changing moisture levels are the main source of post warp, although a discrepancy in liner grade or foundation weight will also likely result in post warp [35].

III. Wash boarding

Wash boarding degrades the printing quality and has a bad overall impact on the board surface's appearance. Wash boarding can be decreased by using thicker liner grades that will not bend as easily and less adhesive. Furthermore, wash boarding may result from excessive liner moisture at the single facer or fluting double facer at the moment of glueing [36].

IV. High low flutes

High/low flutes describe height variations in the corrugated web's fluting. It may result in uneven bonding and has a detrimental influence on the corrugated board's structural attributes. High/low flutes are frequently the root of mechanical problems [4]. Lack of preconditioning, pre-steaming, or preheating can also affect how high- and low-flute structures form. Preconditioning mellows the fibers, which makes corrugation easier and stops high/low flutes from forming. Another issue seen during the corrugation process is broken flutes. Increasing the preheating or pre-steaming is an easy way to solve the issue [5].

V. Delamination

The qualities of the paper and adhesive, as well as the pressure, speed (duration), heat, and moisture parameters in the corrugator process, all have an impact on the complex process of corrugator bond formation [37]. The double-face bond as well as the single-face bond are covered by the bonding theory that will be described. The only exception is the kind and amount of pressure used on the bonded region while it is setting [38] .The single-face bond is only put under pressure for a very brief period of time at the nip between the lower corrugating roll and the pressure roll of the single-facer. For at least six seconds, the double-face bond is placed under lower pressure while the board passes through the hot plate and cooling components of the double-backer [39].

VI. Blistering

An unbounded swelling in the liner surface is known as blistering. After glueing, blisters develop on both single- and double-faced materials. Low starch dosage or low liner moisture both contribute to blisters. Before gluing the liner and fluting together, blisters occur when the moisture content of the liner drops to about 3%. After glueing, the liner absorbs moisture from the glue and the air, which causes the liner fibers to expand, resulting in blisters [40].

VII. Wrinkles

On liner and fluting boards, one will see wrinkles or creases. On liner or fluting reels from the paper mill, wrinkles may already be present, or they may develop at the wet end of the corrugator as a result of wet streaks in the reels [41].

2.6 Enhancing corrugated board strength

2.6.1. Enhancing board strength by Process Control

By using the right control of the single-facer process parameters, the corrugated board will retain the natural strength of the corrugating medium. The flute molding properties of the corrugating media are enhanced by these key process variables. The medium qualities that reduce the flute formation stresses may also improve strength retention after fluting. Reduced caliper and greater stretch at tensile failure are two of this material's main characteristics of the corrugated board printing unit [42].

In double facers, adjustable variables like web tension, glue dosage, preheating, and steam chest pressure set points are typically defined in the recipes. For example, the corrugator maker BHS Corrugated has a device called Quality Data Manager (QDM) that allows users to save grade-specific wet end settings to make board with the same quality attributes easier to produce. In recent years, the corrugated board manufacturing industry has been more interested in developing closed-loop machine controls [43].

Fosber Group uses a closed loop control system based on temperature and moisture sensors at key areas to regulate wrap arm positions, steam pressures along the corrugator, steam showers, all glue gaps, and double backer steam shoe pressure settings. The majority of corrugators in the world lack closed-loop controls. Instead, open-loop control is used to adjust glue dosage, preheating, and double facer pressure shoes based on speed curves given in the recipes [44]. The primary goal of controlling the single-facer medium preconditioning should be to improve bond formation. When the corrugator speed increases, preconditioning should also increase, and when it slows down, preconditioning should decrease.

2.6.2 Paper combination

The distribution of compressive loads on boxes may be impacted by the asymmetrical design of corrugated board. Corrugated boards with distinct weight grades, or variable stiffness levels on the inside and outside linerboards, are referred to as having an asymmetrical construction. In reality, every box is full to the point of bulging outward. This implies that the interior linerboard will be compressed while the outside linerboard will be stressed in tension Maltenfort, explained that load distribution does not differentially influence "inside" and "outside" as long as both linerboards have the same weight classes [45].

A heavier or more rigid linerboard within the box will be able to withstand a higher compression load than it would have if the construction had been symmetrical and the lighter or less rigid linerboard had been in that location. In order to achieve the highest box compression strength, the heavier liner should be inside [46].

The CD of ECT of the combined board is directly influenced by the CD edge crush strength of the corrugating medium. All other things being equal, a stronger compressive strength medium due to a higher basis weight or a modification in the strength improvement process will raise the ECT of the combined board made from the medium fluting. Fluting reduces ECT because the medium's compressive strength deteriorates. The strength characteristics of the medium are diminished during the converting process; however, by retaining more strength during fluting, the combined board strength will be increased [47].

2.7 Factors that Affect the Performance of Corrugated Fiber Board

The selection of materials, such as the type of paper, flute size, and adhesion type, correspond to the quality. These three classes are utilized based on the lifecycle of the corrugated box [7]. It was shown these criteria provided significant impact on the properties of the corrugated board especially in terms of its mechanical strength the combination of paper that made up the corrugated fiberboard is crucial since both liners and flutes will have their own specific target. The corrugated fiber board also may be subjected to damage during the fabricating process [8]. The first part of the process involves variables that control which can significantly affect the properties of the paper if it is not well controlled. After being cut, scored, and slotted during the conversion process, the corrugated fiber board sustains additional damage [32].

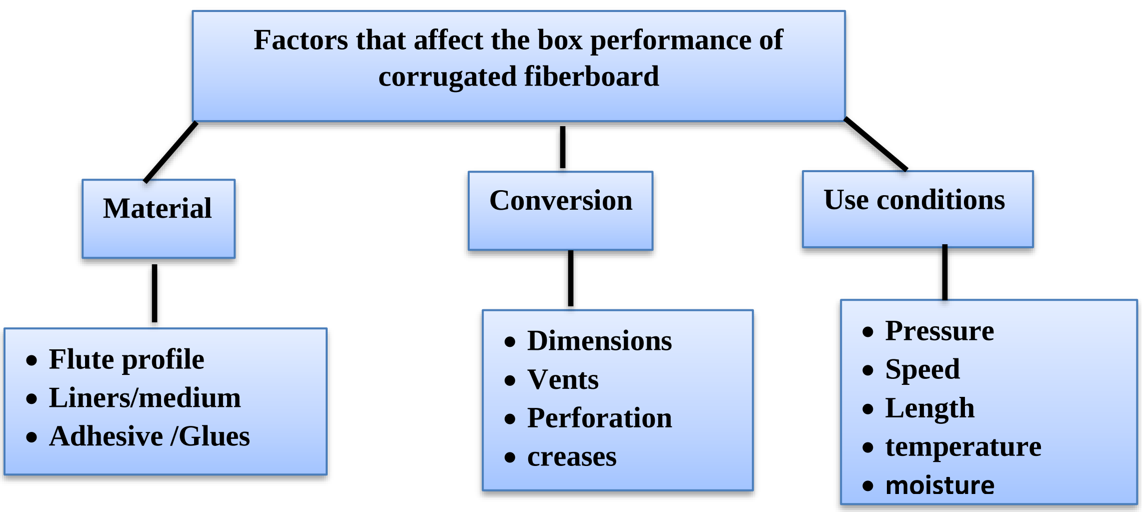


Figure 2. 3: Factors Affecting the Performance of corrugated board/box.

2.7.1 Flute Geometry and Profile

The flute describes the corrugation's wave-shaped paperboard material's structure. The power of the wave is what led to the flute's shape at Figure 2.4, which runs parallel to the package's depth. Additionally, the wave-like shape gives corrugated paperboard packages rigidity and stacking strength, and the hollow space generated by the sinosodial wave-like structure enables air to insulate the contents of the corrugated paperboard box. Flutes typically come in various sizes, known as profiles (Table 2.1). According to Pathare and Opara [24], the A-flute, which is the largest, and the F-flute, which is the smallest, are the usual profiles. The mechanical properties and tensile strength of corrugated paperboard are directly influenced by the flute profiles [4] .

Contrarily, there are unintentional unintended defects to the flute profile that may occur anytime from the production process up until the point of use, such as flute crushing due to blank stacking, printing, and box handling. As a result of this damage, the board's stiffness attributes will be weakened, which will make it easier for the localized failure region to spread swiftly [48]. Damage to the flute's structure will make the board perform worse, giving the chance to comprehend and gauge performance through the flute's morphological changes. The corrugated board flute shape mimics a sinusoidal curve, whose pitch and amplitude can be analytically characterized. However, it is contended that an arc and tangent curve, which takes into consideration the proper take-up factor, describes the geometry of the flute more correctly than sinusoidal, elliptical, and trapezoidal designs [49].

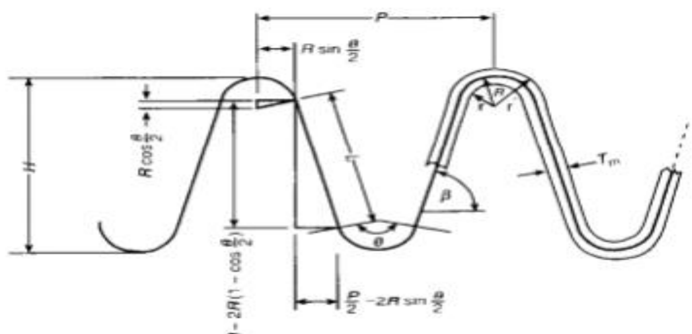


Figure 2. 4: Urbanik to characterize the flute of CFB [49].

By using this method, the flute caliper (h_f – represent as H in the figure), pitch (P) and take-up ratio (α) of the flute are needed as the input parameters to get the flute tip (R), length of the flank (L) and the angle of the flank (β) the geometrical representation with the parameter [18].

2.7.2 Printing Process

Paperboard is frequently deformed in three dimensions and subjected to high magnitude strains during conversion operations like creasing, scoring, and folding [50]. High grammage paperboard cracking is a problem that may be brought on by the way the folds are made at the creasing and it is a crucial mechanical characteristic of paperboard die cutting [51] .

When paperboard is creased, a shear-induced delamination is created into the paperboard structure, which weakens the paper fiber and reduces the stiffness of the paperboard around the folding line. Cracked folds can weaken corrugated fiber board and the packaging, which can reduce their strength and appeal to consumers [50] [52]

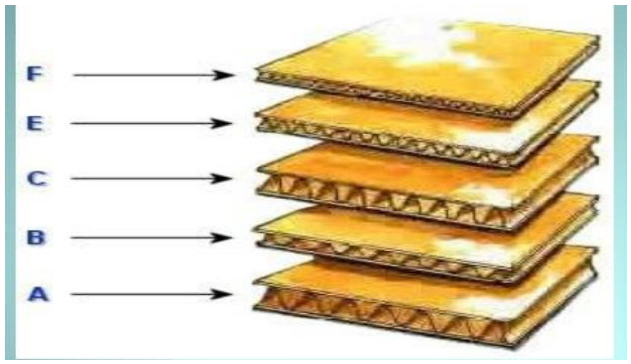


Figure 2. 5: Different flute profiles [52].

Table 2. 1 : Geometrical Properties of Flute Profiles [52]

Flute type	Pith, P (mm)	Corrugations per meter	Flute Height (mm)	Take up factor
A	8.3-10	100-120	4.67	1.54
B	6-6.5	150 - 185	2.1 - 2.9	1.37
C	7-8	120 - 145	3.5 - 3.7	1.20-1.43
E	3-3.6	290 - 320	1.1 - 1.2	1.28

2.7.3 Moisture

Quality should be controlled at each and every step in in-factory by inspecting the percentage level of the moisture of paper board to be functional [53]. During the testing, it was discovered that the C flute consistently failed before the B flute, independent of the temperature or humidity. The larger number of flutes per inch can be used to explain the B flute's greater power. C flute only contains 42 flutes per inch, compared to B flute's 52. Since the C flute has more exposed surface areas to moisture per inch than the B flute, it should logically be able to absorb more moisture before losing strength. Paper's moisture content has a significant impact on its characteristics when paper is dry; it usually includes around 5% moisture [54].

2.8 Corrugated Box Performance and Testing

The efficiency attained during the production of the paperboard and packaging, as well as crinkling and packing activities, all had an impact on the performance of corrugated paperboard [55]. Furthermore, the strength of the package during handling, shipping, storage, and point of sale of packaged goods as well as in customer use are related to the performance characteristics of corrugated board packaging. Several of the several measurements and tests used to describe the multiscale mechanical strength of corrugated fiber board packaging.

Performance testing of corrugated paperboard packaging, with a focus on the production process and environmental elements that influence corrugated board packaging strength. Testing the quality of corrugated fiber board and its numerous components, keeping good control of production operations, and environmental factors like moisture, humidity, and temperature are necessary for a better understanding of the performance of corrugated board packaging [56].

2.9 Ring Crush Test Ring

The ring crush resistance of a paper strip shaped into a ring with a standardized length and width is assessed using ring crush tests (RCT). Compared to the Short-span compression test, the RCT is a crucial and pertinent indicator of package stacking ability, according to the Australian paperboard industry [57].

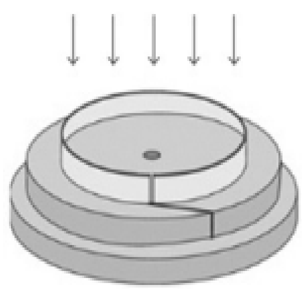
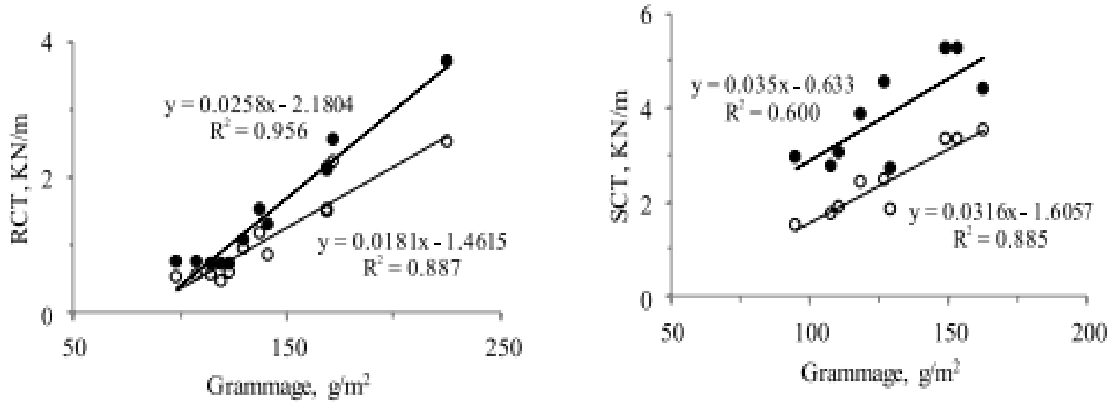


Figure 2. 4: Test specimens in ring formation of RCT method [57].

The coefficients of determination for the linear connections between all of the strength parameters and grammage were from 0.887 to 0.956 for the liners fig.2.5 a, and from 0.6 to 0.885 for the fluting-medium fig. 2.5, b, respectively. In general, the influence of structural density on the strength properties was either non-existent or had a weakly positive connection for both the liners and the fluting-medium. This shows that grammage is a more accurate indicator of the impact of recycled paper's bulk structure on paper strength [7]. This study shown that regardless of the paper category or subcategory to which they belong, the range of packaging paper grades made from heterogeneous recycled pulp may be identified by their grammage. The findings can be applied to make quick predictions of recycled paper's strength characteristics based on grammage, allowing for practical use in the right corrugated packaging applications [58].



a) b)

Figure 2. 5: a and b show the connections between liners and fluting grammage of mechanical characteristics. Observation CD direction [7] .

2.10 The ECT of Corrugated Board

Due to nature of box failure, McKee stated that the material at the edge fails at load intensity equal to the intrinsic corrugated board property. McKee stated that box failure is triggered by edge failure of the corrugated board. In addition, ECT data was relevant to total BCS as it reflected some of the effects the manufacturing process and the inherent material properties of corrugated Nordsrand state that the edge stiffness influences box failure load is it affects the load distribution on the top and bottom edges of the box when the panels buckle [16]. Hahn et al. Have found that the most effective way of increasing the collapse load of corrugated board panels is by improving the compressive properties of the panels which means an increase in the ECT value [12].

Paper Science and Technology Institute, Pressure, high/low flutes, leaning flutes, single-face pin adhesion bond strength, crushing, are corrugated board quality flaws that are connected to the combined board ECT using a mathematical model of the experimental data on regression equation. It was discovered that the variables added up for instance,

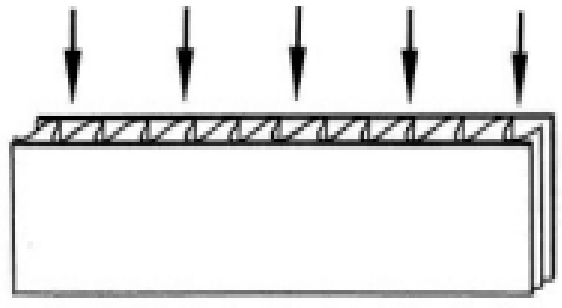


Figure 2. 6: Test specimen consisted of cutting samples parallel to the flute direction (CD).

even though both flaws lower the combined board's caliper, [28] the ECT loss from crushing will be added to the ECT loss from leaning flutes. When two variables interact, their combined influence might be either higher or smaller than the total of each one's individual effects.

The link between pin adhesion and box performance can be affected by basis weight. Due to increased bending and shear pressures on the glue line, heavy weight linerboards may reduce box strength more than grades of 4% or less. Pin adhesion loss might worsen the impact of intermittent glue application and glue line skipping on ECT and BCT. A 0.4-inch glue skip can result in a 17% ECT loss, whereas a 0.1-inch skip can result in a 4% ECT loss [59]. Moreover, the impacts of glue line skip plus a heavy board would have a more significant effect on compression performance. There are even more variables that could have an impact on how pin adhesion and compression strength relate to one another. Mismatched board components, asymmetric box structures, and fragile bonds are a few of these that could cause a greater than expected change in compression strength due to changes in pin adhesion [5]. Therefore, lacking these specific circumstances, it would not be wise to attribute compression strength losses to pin adhesion.

At figure 2.7 ECT versus PAT at 300 and 500 feed per minute the linear trend of R^2 is 0.18 and the lower figure has good relation but it does not data showed on the graph. Corrugator bond strength has a direct impact on corrugated board compressive strength. A 10% reduction in pin adhesion strength results in a 3.3% loss in the combined board's Edge Crush Test and a 2.5% loss in top-to-bottom box compression [5].

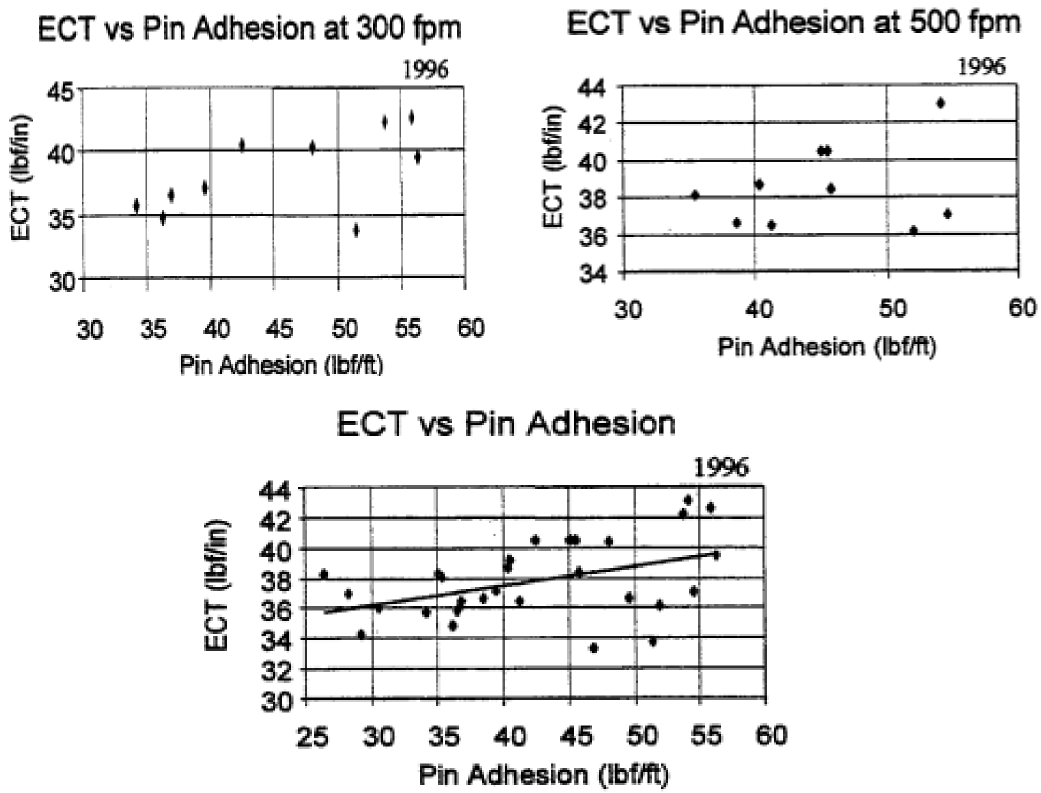


Figure 2. 7: The trend-line based on linear regression a positive slope is indicated, the relationship of ECT and PAT [59].

The following observations regarding how the combined board CD Edge Crush Test and the corrugating medium interact and relate summarized by Betika corrugated medium reference[5].

- Measuring and controlling the gap settings at the various pinch points in the process is a potential substitute strategy for managing flute crushing in the box plant.
- A 10% modification to ECT results in a 7.5% modification to box compression.
- The CD ECT of the board strength of the corrugating medium has a direct impact on the strength of the combined board. A stronger compressive strength medium caused by a greater basis weight or a change to the paper mill's strength improvement method will, all other things being equal, increase the ECT of the combination board made from that medium.
- The industry's inability to come to terms on a standard, accurate, and precise correlation equation between the medium CD crush strength and the combined board CD ECT may be partially explained by the effect of these medium material qualities and process variables on the ECT.

2.10.1 Buckling and Bending of Corrugated Board

The case of corrugated board under vertical load is applied to beam mechanics in order to develop standards for test specimen height for ECT. The streamlined method utilized here is anticipated to offer some approximation of the impact of specimen height on ECT, even though the strains involved place the compression phenomenon into a non-linear zone of elasticity. Because the board samples utilized in a series of creep behavior investigations had slightly different dimensions from those used in standardized ECT, it was necessary to quantify how sensitive ECT was to specimen height in order to validate the results [60]. If failure results in the creation of a crease and the peak load is not impacted by any bending of the test sample, compression strength has been successfully evaluated. This means that the test specimen's compressive strength ECT should be lower than the test piece's buckling load. When this requirement is met, the specimen breaks down via compression rather than bending. When subjected to vertical loads, corrugated board behavior can be roughly modeled as a sandwich panel by ignoring the medium's structure and other variables that contribute to flexural rigidity The failure mod is indicated by the dotted curve, which represents the buckling load and the height over which beam bending is anticipated to predominate [61].

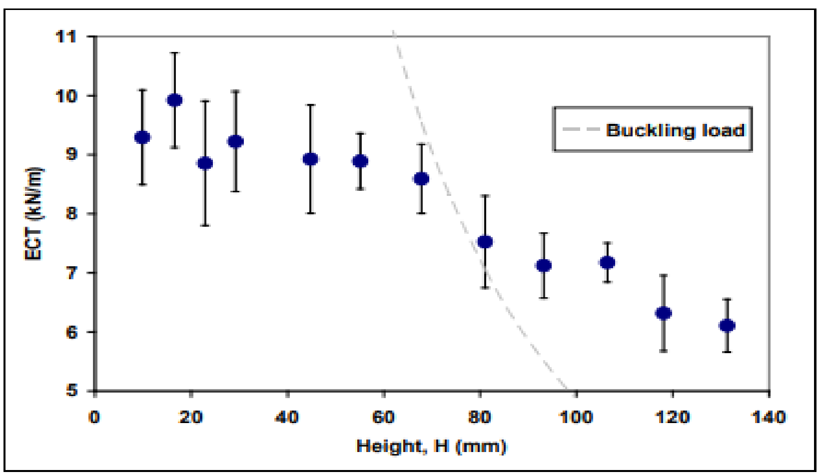


Figure 2. 8: For C-flute specimens, ECT is compared to the span length.

2.11 PAT (Delamination) of the Corrugated Board

Since the speed of corrugation and adhesive quality have a major impact on package stacking strength, this is an important fabricating component. The properties of the liners and fluting medium, the rate of corrugation, the amount of starch solids composition of the starch mixture had no effect on how strongly the liners adhered to the fluting medium [56]. However, the amount of starch used had a specific impact on the strength of the liner adhesion. Although it should be noted that excessive adhesive application during the bonding process can negatively affect corrugation quality, corrugated paperboard may also experience wash boarding, which can result in subpar print quality, warping and board crushing as a result of the fluting medium becoming moist during slotting and scoring [25].

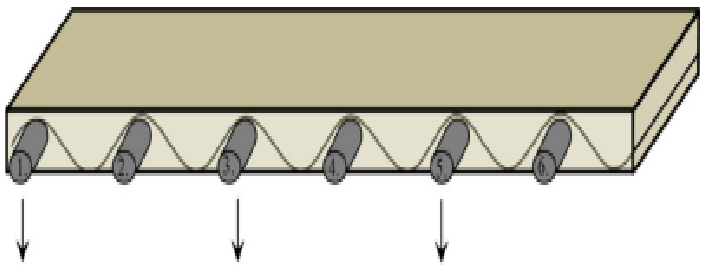


Figure 2. 9: Pin adhesion bond strength testing schematic diagram [37] .

One of the series pins done contact the last series of pins are solely in touch with the linerboard that needs to be separated since the fluted medium is attached to the linerboard. According to Fig. 2.9, pins 1, 3, and 5 are attached independently to an upper compression platen, while pins 2, 4, and 6 are attached to a lower platen, allowing the bottom line to be separated from the remaining corrugated board when the platens advance. Delamination problem is one of the lowering factors of decreasing the strength of the performances of the board and the common problem Sometimes, when higher grammage paper is used, the heat may become insufficient [3].

Temperatures, moistures, tensions, speeds, and nip roll pressures are just a few of the operating factors that must be tuned in order for there to be effective bonding. Additionally, the mechanical alignment of the corrugating and adhesive applicator rolls mechanisms as well as the properties of the adhesive formulation are crucial. By taking into account the corrugating process' guiding principles, it is possible to determine how all of these variables and parameters are connected [62]. Adhesive had also a great impact on the performance of the corrugated box, to decreases the compression strength of the final box, Each layer should full fill the mechanical properties, considering corrugation circumstances, adhesive composition, component porosity, or hydrophobicity, as well as board quality, can all have an impact on this value and the performance of the resulting box can be improved as per the result find, such as, tension, production speed, type of glue, types of paper and for sake of penetrating glue inside, viscosity [37].

Generally speaking, the viscosity of adhesives decreases every time they pass through the circulating pump, at this time, the new adhesive should be mixed. In addition to this gelatinization temperature refers to the initial temperature needed to change starch binder into paste. And it is the key factor to maintain high-speed production, besides adjusting the dosage of caustic soda and heating method, proper addition of some additives can also achieve the same effect. The gelatinization temperature should not be too low; otherwise, it will cause the gelatinization of the adhesives in the circulation process and affect the fluidity of the adhesives [63].

According to Kroseschell observations to summarizing the classification of the failure in bond strength tests ("pin adhesion") at five different places: first, in the adhesive itself; second, at the adhesive-medium interface; third, inside the medium (a condition known as "decapping"); fourth, at the adhesive-liner contact; and fifth, inside the liner [58] [64].Fig.2.10. Failures within the liner always produce the toughest bonds, and failures within the adhesive itself were the most fragile, producing the lowest pin adhesion values modes in “Pin Adhesion” bond strength tensile testing of the (bottom) single-face linerboard [65].

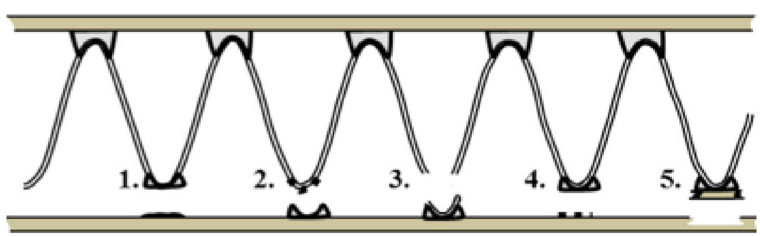


Figure 2. 10: Section of combined corrugated board showing different failure.

Based on the different results obtained with speed and paper as well as the printer use, delamination is a characteristic input for the improvement of the strength of the box performance need [59].Corrugated board edge compression strength and vertical load box compression strength demonstrating how all these qualities can be lowered by bonding flaws. Additionally, research was done on the double-backing process' bonding mechanisms in relation to hot plate contact, temperature, and other factors exhibited [60]. The correlation between pin adhesion values and the speed of the single facer, the temperature during pre-conditioning, the depth of adhesive penetration, the kind of bond failure, and the paper moisture content [65] .

2.12 Box compression Strength

The BCS of corrugated box is depended the ECT of the board and is flexural properties in addition research has the shown that the transverses shear stiffness and structure of the box, i.e. creases and flaps affects the BCS of the box [66].The quality of the paper used to construct the board and its structure as well as the mechanical process of board manufacturing affects the BCS of a box.

2.12.1 The Structure of Corrugated Boxes

The creases account for 90% of box deformation caused by compression forces; the crushing strength of creased board is roughly 50% of ECS. The weight distribution of the top and bottom edges when the box panels buckle depends on the stiffness of the creases, which is a crucial characteristic [61]. The creases of the corrugated box result in eccentricity of the applied load, which reduce the load carrying ability of the panels. Nordstrand investigated the effect of load eccentricity of 25% of the panel thickness result in a 15% reduction in panel compression load. In addition, an imperfection of ten times the board thickness resulted in a 40% decrease in the panel collapse load. Norstrand has also found that design parameters, such as the slenderness ratio and stiffness asymmetry, have an effect on the collapse load of corrugated board panels [67].

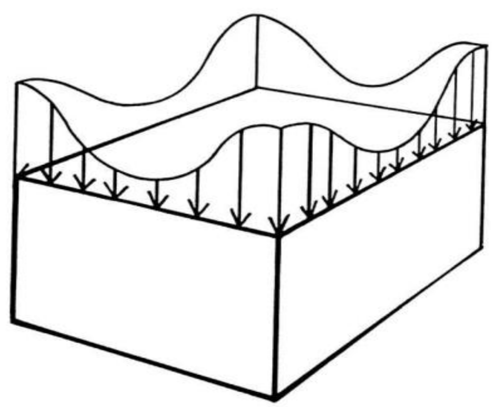


Figure 2. 11: The stress distribution around the edges of a corrugated board box under load [57].

Due to the fluted medium's ability to flex like a bellows, the compression load must only be carried by the linerboard facings. The medium ties the linerboard facings together so they function as a single structural unit and aids in supporting the facings at the bonded location. The linerboard is divided into a number of short, stacked segments by the bond locations. Instead of the power of the medium itself, this impact is determined by the distance between the flutes. The impact of the ECT strength on a corrugated box's top-to-bottom compression strength makes it significant

[68].The combined compressive strengths of the test liners and the fluting medium materials employed in its manufacture have been linked to the CD ECT of corrugated board, of course, the flute draws factor's impact is included in the corrugating medium's contribution.

Most compression testing research has been done on corrugated fiberboard boxes since the walls of boxes are typically expected to hold the weight of a stack. Known variables that affect the compression of corrugated fiberboard boxes. However, it should be emphasized that typically the item inside the box aids in supporting the stacked burden. For instance, packaging for items like canned goods, glass jars, and plastic bottles may not require any compressive strength from the shipping container at all and may instead rely on the strength of the product itself [69] .

2.12.2 Box Failure

Corrugated board failure is dominated by material and structural failure. Material failure involves failures of inter fiber bond. Nordstrand conducted compression tests on panels and predicted the failure load using the thai-wu failure criterion. A 6% difference between the analytically determined and experimentally determined failure load led him to conclude that collapse of corrugated by material failure of the inner [67] . Local instabilities of the facing and core can interact with the failure propagation. Structural failure involves facing instability i. e local bucking. Local bucking of the faces dominates corrugated board failure when the box experiences high transverse and normal shear stresses. Because of its relatively even force distribution along its perimeter upon failure, the shallow box that does not buckle has a higher strength [70]

The difference between local and global buckling must be made, When the linerboard buckles in between the flute crests, it is referred to as local buckling. When the entire panel buckles, this is known as global buckling. A wrinkle that begins close to a corner and travels diagonally toward the panel's center forms at the point of collapse as a result of the local buckles [71]. However, during manufacture, components of combined boards may be damaged by compressive forces. For example, when the board is run through printing or converting machines, perpendicular forces applied to the surface of the board may cause considerable sidewall compression. As a result, the board does not possess the ultimate strength obtainable from its components. The asymmetrical construction of corrugated board can also influence the distribution of compressive loads on boxes [68]. Asymmetrical construction refers to the corrugated boards that have different weight grades, i.e., different stiffness levels on the inside and outside linerboards.

In practice all boxes are filled, so that any bulge is outward. That means the outside linerboard will be stressed in tension while the inside will be in compression. If the construction is asymmetrical, then a heavier or suffer linerboard inside the box will accept a higher compression load than if the lighter or less stiff linerboard had been in that position. Therefore, the heavier liner should be located inside in order to acquire the highest box compression strength [72].

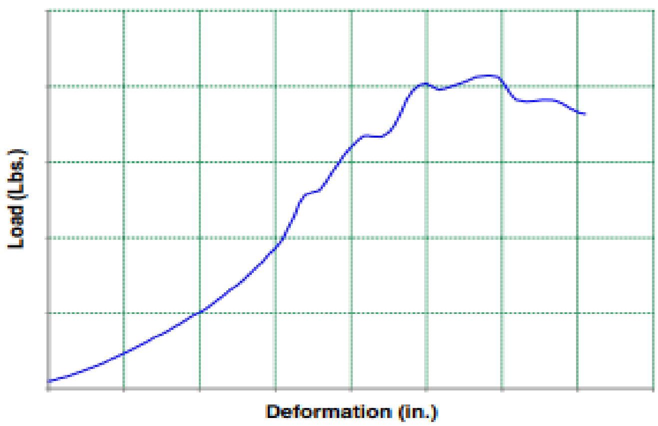


Figure 2. 12: The load to failure as a function of the deformation under load [8]

2.12.3 Box Strength Prediction Formula

Box strength prediction is important due to the fact that today's consumers want an optimized product. This is due to the fact that consumers require lighter packaging materials [73]. This result in box manufactures needing to optimize their products and cut the cost of the packaging. In addition, recent environmental concerns have also increased the pressure on manufactures for better utilization of raw materials. This requires a thorough knowledge of paper properties and their effect on corrugated box failure. Even though box strength is well characterized by BCT prediction techniques, based on board and paper mechanical properties as well as board geometry, to predict BCS [74] [75].

$$BCT = 5.87 * ECT * \sqrt{P} * Z$$

With,

ECT: Edge Compression test (KN/m).

P: Perimeter of the box (mm).

Z: Caliper of combined corrugated board (mm).

According to the McKee equation, the compression strength BCT of a corrugated board box with the regular Slotted Box (RSC) design can be predicted from knowledge of:

1. The edgewise crush resistance of the corrugated board, the ECT-value in kN/m
2. The periphery of the box, Z in m. In general, the so-called McKee formula.

The structure of these equations clearly highlights the importance of different material parameters on box performance. ECT, or the edge crush strength of the combined board, has the largest role in estimating box strength. Measuring ECT attempts to quantify the inherent material strength of the complex corrugated board structure, The McKee equations are the recognition that these parameters are linked to the dimensions of the box. A bigger box can support more load although this seems an intuitive statement, box strength is not linearly related to box size because the bulk of the load is supported primarily by the corners, where the box panels meet [8].

2.12.4 Disadvantages of the McKee formula

The disadvantages of the McKee formula are: -

- It is only applicable to RSC style boxes where the length is not greater than three times width and the perimeter is not bigger than seven times the depth [76].
- The formula showed an error of 6.1% from box grades with average mechanical properties. In addition, the use of non-RSC style boxes has raised issues as to the acceptability of this method with regard to both strength prediction. The Maltenfort equation shows much better sensitive to box length and width affects than the McKee formula. In addition, the McKee formula only takes into account bending stiffness and ECS. As corrugated board is considered an orthotropic material, the influence of transverse shearing affects and material properties such as poisons ratio and tensile moduli not be underestimated. In addition, the use of non-linear material theory has shown to be more sensitive to different box styles and is consistent with the Maltenfort results [76]. This has led to a number of different methods for corrugated board an ultimately box strength prediction.
- It does not take into account manufacturing factors such as gluing, crushing and does not allow for box optimization [61].
- The McKee relationship is constrained as the box perimeter grows, most likely as a result of the altered length-width ratio [18].

2.13 paper compression strength

The ECT strength is important because of its effect on the top-to-bottom compression strength of corrugated box. The combined compressive strengths of the linerboard and medium materials employed in its manufacture have been linked to the CD ECT of corrugated board. The contribution of the corrugating medium includes the effect of the flute draw factor.

The relationship between the ECT-value and the compression strengths of liner and fluting medium can in general be written Maltenfort Equation:

$$ECT=K\ (\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{C,f})$$

Where σ_c is the compression strength L_1=liner 1, L_2=liner 2, f=fluting medium, (α is the fluting take –up factor and k is a constant [77].

"K" Theoretically the sum of the compression strengths of liners and fluting media should be equal to the ECT-value so that k=1.28 or possibly slightly lower in order to compensate for the reduction in compression strength of the fluting medium caused by the corrugator. Because of the difficulty in determining the ECT of the board and the compression strengths of liner and fluting medium under exactly the same measuring conditions have to live with a factor "K" which is a function of the chosen test methods. The statement that the sum of the compression strengths of liner and fluting medium is equal to ECT" can be valid only if the staring to fail urea is equal for both liner and the fluting medium and this is seldom the case methods for the routine determination of compression strain to failure are in any case lacking. The so-called Maltenfort equation provides the general structure of the mathematical model to predict the ECT of the board from the compressive strength of the liners and fluting medium. In order to examine the compressive strength of corrugated board in relation to its component parts, this model provides good forecast accuracy and it is frequently used in industry to compare the characteristics of corrugated board with paperboard properties [66].

The challenge is to find a more representative value, which would help in more accurately predicting the board and subsequent box performance, regardless of the paper compression strength test that is used. This is a result of testing blunders, test method limitations, and production variations at the corrugating plants. Moreover, the aforementioned claim that k is equal to unity would only hold true if the strain at which both the liner and the fluting medium will fail is the same, which is rarely the case examined and discussed the variables influencing the preservation of compressive strength during fluting, or the effect of the fluting process on the constant k.

According to their findings, the fluting procedure causes corrugated board to lose 15–20% of its ECT potential. This happens as a result of the fluting process, which under hot and cold forming conditions significantly reduces the medium's edgewise compressive due to the fabrication of paper bending and tension strains fluting places on the medium paper, the strength is reduced. High stresses are applied to the material during the converting process [45].

The boards are also steamed while being manufactured, which releases internal stresses in the sheet [57].This may result in a 5–15% reduction in the sheet's elastic modulus and compressive strength. It should not be surprising to learn that the combined strength of the paper components is higher than that of the corrugated board created from them as they are sampled before any treatment. It is impossible to estimate the magnitude of the harm done to paperboard as a result of manufacturing conditions, although Seth suggested that it would vary for various plants and within a plant for various flute [60]. Another element of the flute is the take-up factor, which measures the proportion of the length of the fluted geometry to the length of the unfluted geometry and specifies how much paper was used to make the flute [45] . The varieties of flutes specified in table 2.1 are seen in Figure 2.13.

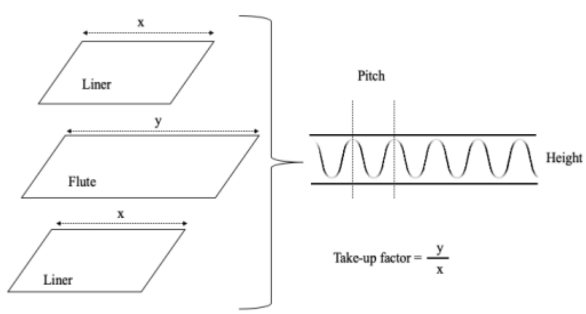


Figure 2. 13: Diagram showing the corrugated board's height, pitch, and take-up factor [27].

2.14 Paper and board property

The thickness or "caliper" of the paper or board determines how dense and bulky it is. A paper calliper measures the angle between two flat parallel surfaces at a pressure of approximately 98 kPa, or 1 kg-force per cm^2. A micrometer is frequently used to measure it. Among the properties of paper board basis weight caliper density and uniformity of all other properties in both the across the machine and cross machine directions are probably the most important for paperboard [78]. Basis weight is important to the user who requires a certain surface area for the packaging operations. Caliper can influence the machinability or performance in board making machines. Caliper is also important in controlling density of the board and also have an influence on stiffness and scoring [79].

As the models have been improved to incorporate all crucial structural and component aspects, the interactions between paper and board properties have grown increasingly complex. The most straightforward method cited by Wisconsin [4] is to include the compressive strengths of the different parts (test linerboards and fluting), enabling for the fluting profile type to be drawn. This strategy has strong predicted accuracy when based on the right statistical weighting variables, therefore it would be employed in the current investigation. The author also stated that the quality of corrugating converting affects the board's edgewise compressive strength.

2. 15 Factor of Safety

The safety factor, in theory, is an estimation that advises the designer on how much more robust a container should be made than the actual weight on the bottom container in a load depending on the variables the container will be subjected to, including its design. According to Compression Test Method the strength characteristics of corrugated boxes cannot be predicted when used within their intended parameters. Corrugated is significantly impacted by variables like humidity and temperature variations [54]. In addition, the strength of the flute structure can be decreased by shocks, vibration, compression, and printing. The carrying capacity of a corrugated box can be reduced by up to 50% as a result of the vertical edges of one box stacked on top of another being out of line. Distribution operations can significantly change the strength of a corrugated box.

Meaning that a higher safety factor is needed the more challenging the shipping and distribution environment is. To make up for the losses caused by the components of the distribution environment, a safety factor is multiplied into the calculation humidity [66]. This container has for safety factor. Everyone in the sector has different opinions on how high the safety factor should be, but a general guideline in the corrugated industry is between 3 and 5. This indicates that a corrugated container needs to be built to be 3 to 5 times stronger upon initial testing that the greatest load it will have to support [54].

2.16 Summary of the Literature Review

The speed at which this operation can be transformed without cracking of the medium is one of the limiting factors in the manufacturing of corrugated fiberboard, and is a function of the "runnability" of the corrugating medium used. The most crucial role of the manufactured paper is to provide enough strength to the completed box to withstand the intended use. The paperboards are also steamed while being manufactured, which releases internal stresses in the sheet. This may result in a 5–15% reduction in the sheet's elastic modulus and compressive strength. Given that the paper components are sampled before any treatment, it shouldn't come as a surprise to learn that their combined strength is higher than that of the corrugated board made from them. It is challenging to estimate the magnitude of the harm done to paperboard as a result of manufacturing conditions, however suggested that it would vary for different plants and within a facility depending on the flute type.

The ECT value can be increased and thereby the BCT-value for a box of a given size by using liners and fluting media with a higher compression strength or by a higher grammage of identical raw material. Web tension is a crucial component in the production of corrugated paperboard since it has been recognized as one of the components that improves the flute moulding properties of the corrugating fluting medium.

2.17 Gap of the literature

It is mostly not done (variables such as the reel size, with fabricated speed, number of printing home) have different value of compression strength as of temperature, pressure and moisture during the manufacturing of CFB.A number of studies have been conducted on temperature, moisture, and similar properties on its effects on the strength of the board. Regarding the mechanical performance between recycled and virgin paper, various advantages and disadvantages they have been studied in depth in various studies. At the same time converting the process, the different mechanical properties of reel size, speed, and adhesive effects with interacting of paper properties, the resulting negative and positive aspects are not explored. They also have a significant impact on the strength of the board, the way to reduce the board defect and effects by using fabrication process to improve their strength at the variables has been shown in this study.

CHAPTER THREE

MATERIALS, METHOD, AND EXPERIMENTAL PROCEDURE

3.1 Introduction

In the manufacturing of corrugated board, mainly using test liner and fluting paper, to fabricate B-flute, C-flute and E-flute, each of which has different geometrical profile and strength of the final box, there is variety of corrugated boxes that use, and to verify this, experiments have been done based on the samples manufactured by C-Flute, associating different reel sizes with different operating speeds. The corrugated board varies in strength depending on the variables in which they are manufactured. In this thesis, based on the variables that can improve the strength of the corrugated fiber boards through process, RS165, RS185, RS205 and RS220 cm, paper sizes were collected and the samples fabricated at a production speed of 50, 65, 80, 95 m/min.

To determine the RCT of the paper, the samples of paper and board were then painstakingly labeled for each combination and in accordance with their location (L_1, L_2 linerboards, and F for fluting medium paper). To achieve accurate CD compression strength evaluation, cross-machine direction (CD) was also indicated on all papers. The fluting profile types that were encountered to each board combination were also noted for later evaluation of the medium paper take-up factor. The experiment conducted to see how much the strength of the corrugated box will be reduced across different process variables. This reduction is linked back to the factors that might contribute to the strength of the fabricated board. BCT, ECT, and PAT, RC tests will be performed at different variables of the C-flute corrugated board.

3.2 Sample Notation of the Corrugated Board

The notations for the fabricated board samples tasted are local paper, all the board combinations refer to both test liner and medium. Such an expression indicates to all or those mentioned here that the difference in reel size and manufacture is according to the said figure, even though they are written in different sizes and numbers.

- RS165/65/5…. reel size 165 cm fabricated at 65m/min.
- RS165/65/5…. reel size 165 cm fabricated at 65m/min printing with 5 color flexo printing machine.

- RS185/50/65/80/95... reel size 185 cm fabricated at 50,65,80 and 95m/min.

3.3 Paper Type and Geometric Parameters of Corrugated Board

- The corrugated paper was Manufactured in 2022 at a local paper mill Company in Ethiopia.
- The machine Corrugator size is 220 cm.
- Corrugated board samples were also used to delaminate the fluting(s) from the liner boards in order to ascertain the precise take-up variables for the fluting profile at the case company, according to this the take up factor is 1.25.

3.4 Data Collection

In order to make this work a reality, the experts and officials in the profession were interviewed and information was collected by asking questions. From unlimited paper packaging company, operation manager, production & quality manager, as well as from Burayu packing and printing industry, operators, supervisors, production head, quality expert and quality service head, questions are asked that are relevant to the work done, the important information related to fabricated corrugated board process were presented. In order to realize the intended purpose of the paper, those data collection methods were used then finally experimentally examined and justified.

3.5 Testing Conditions

All samples were conditioned and tested in accordance with Tappi T 402 standard conditioning and testing atmospheres for paper board, pulp hand sheets, and related samples due to the hygroscopic nature of paper. All corrugated board samples were subjected to the required conditions of 50.0%±2.0% relative humidity (RH) and 23.0±1.0ºC for a 24-hour period in accordance with this standard [80] [81] .

3.6 Material Used

The test liner and fluting of all the board combinations manufactured in 2022, were the grades of paper recycled local paper, tasted Burayu packaging and printing industry commonly uses these paper grades to fabricate C-flute, B-flute and E-flute at the board combination of three layers, five layers, and seven layers. The testing procedure are preparing according to Tappi, ISO & FEFCO, standard T 494 om-01 [82].

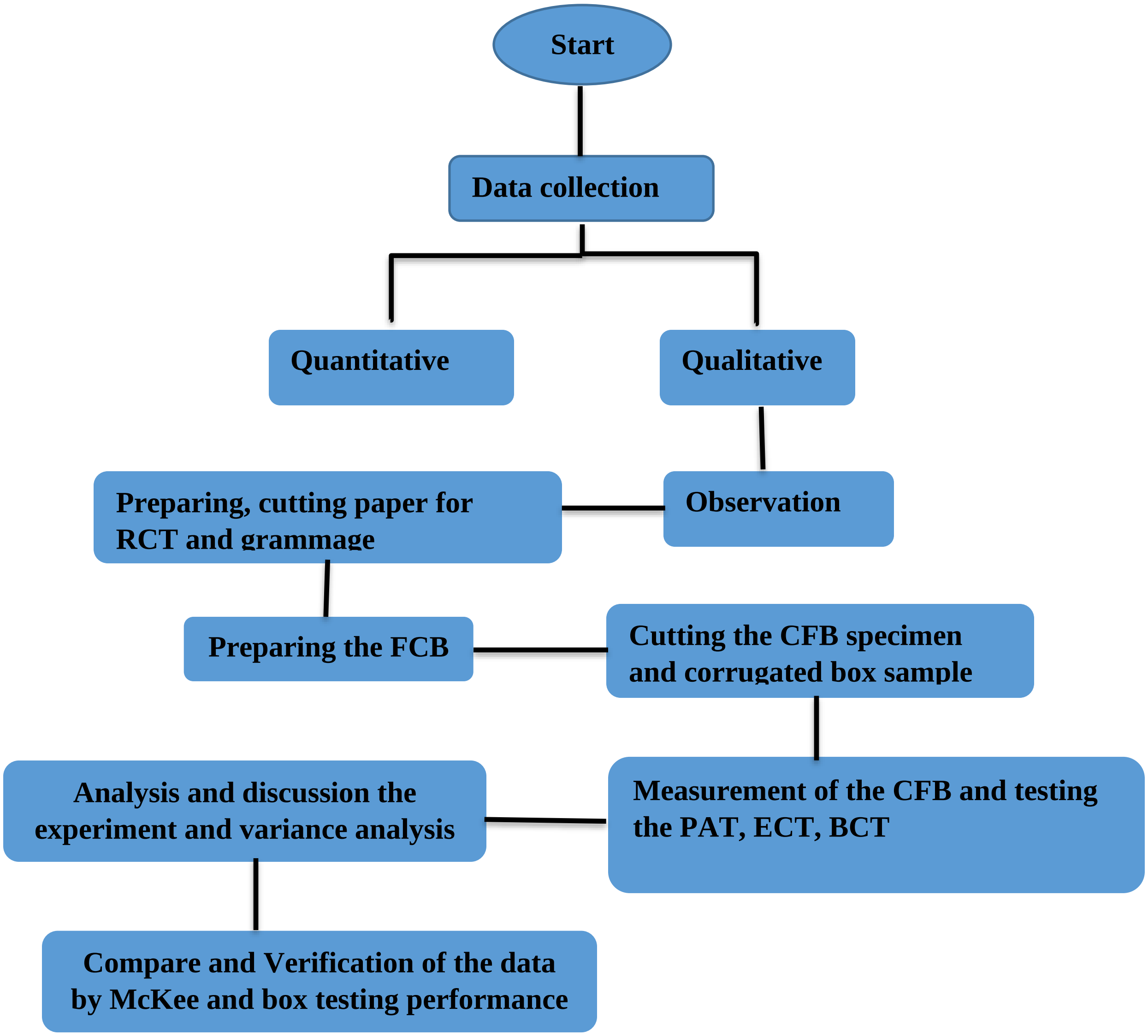


Figure 3. 1 : Methodology.

The experiment conducted to see how much strength of the corrugated box will be reduced across different process variables. This reduction is linked back to the factors that might contribute to the strength of the board. BCT, ECT, PAT, test performed at different variables of C-flute corrugated board at the same time the RCT at the CD direction with paper substrate measured. To determine the precise take-up factors for the fluting profile at the case company the corrugated board samples were also utilized to delaminate the fluting(s) from the linerboards.

The corrugator size is 220 cm, but in this machine, boards of different sizes are manufactured using from 130-220 cm paper size. the result obtained from the experiment discussed as well as calculations that were performed using the data obtained from the Burayu packaging, Addis Ababa institute of technology and unlimited packaging laboratory. The result of the specimens of the corrugated paper test results of PAT (Delamination), ECT, and BCT test was experimented done at different runnability of corrugated board was determined, and predicted the BCT, discussed due to the performance of the corrugated board. the hygroscopic nature of paper, all specimens were conditioned and tested according to Tappi T 402 standard conditioning and testing atmospheres for paper board, pulp hand sheets and related products. According to this standard, all corrugated board specimens were conditioned under 50.0%±2.0% relative humidity (RH) and 23.0± 1.0^{o}C for 24 hours. The test liner and fluting of all the board combinations fabricated in burayu printing and packaging were the grades of corrugated recycled paper manufactured were by Kuriftu paper mill industry in Ethiopia at Adama town., The testing procedure are preparing according to Tappi, ISO & FEFCO, standard and ISTA2 [83] [81] .

3.7 Experimental Work and Procedure

3.7.1 Apparatus

Burayu packaging and printing factory has the following laboratory equipment on hand, was employed for the experimental laboratory work.

- For the fabricated board paper sample, the RCT Guillotine, serial No. BPP-LE-01-009, was utilized to cut the paper specimens to the required size for RCT (152.4 x 12.7mm).
- Board specimens of the required size were cut using the PAT and ECT sample cutter Global, serial No. LE-02-002, for testing on edge crush and pin adhesive (delamination).
- The thickness (caliper) of paper samples prepared in a standard environment was measured using a precision micrometer with serial number YQ-Z-10.
- To obtain oven dried paper and corrugated board samples, an electric oven with the serial number BPP-LE-01-008 was utilized.
- Ring crush tester, model GCCE-2010 was used to perform Ring crush on the precut and treated at sample paper of the fabricated corrugated board.
- PAT and ECT compression tester, model DC-YSY3000A- 2010, was used to performed PAT and ECT compression tests on the precut and preconditioned at different variables of the fabricate corrugated board sample.
- Electronic balance digital scale, No. BPP-LE-01-001 was used to determine the paper samples weight of the fabricated corrugated board paper.

- BCT compression tester, 50 KN computerized electronic universal testing machine, model: ETM -50, 2021, in AAIT, machine, was used to performed box compression tests on corrugated box samples.
- BCT compression tester, 5 KN computerized electronic universal testing machine, model: M 500-25AT, in unlimited packaging plc, machine, utilized to perform the compression tests on different heights of the corrugated box samples.
- ECT compression tester, a computerized electronic testomeric material testing machine, model: M 350-5AT 2021, in unlimited packaging plc, was used to perform edge compression tests on different heights of corrugated board samples.

3.8 Experimental Design

The experiments design used in this study was used two group design the first is to analyze the mechanical and adhesive strength, the corrugated boards and boxes were collected from the fabricated boards at the reel size of 165,185,205, 220 cm at the manufactured speed of 50,65,80 and 95 m/min. in order to know the physical properties of the paper compression strength of the liners and the medium were collected directly from the paper reels at the same time board samples collected and delaminate from the boards to establish the take up factor . The second design were evaluating the fabrication process in order to know their linear mathematical relationship depending on the converting process at the fabricated speed of 50 and 80m/min to determine the effect of adhesive strength with the edge crush test, the adhesive strength with displacement ,the edge crush test with board caliper , and two test liners and one fluting from reel paper and sheets were collected to establish the paper compression strength with grammage, and thickness to establish the accurate board performances and to quantify the board enhancement during fabrication.at this study four variables were used such as paper reels, fabricating speed ,paper property and adhesive glue according to ISO 536,ISO 534, for paper grammage thickness respectively .The paper ring crush test ,edge crush test ,pin adhesive test samples were used to conduct according to ,Tappi T822,FEFCO No-8 and Tappi T821 om-17 respectively. To investigate the performance some boxes were collected tested by dead weight and box compression test were experimented at according to Ista 1A and Tappi T-804 om-02 standard. To verify the compression strength of the paper and the corrugated box compare their result by Maltenfort and McKee equation were used to predict the combined edge crush and box performance. The collected board and samples were treated in order to minimize errors according to Iso, Tappi and FEFCO standard. The effect and cause of reel size, fabrication speed, material property and adhesive were clearly experimented in order to know their chartcerstics of the compression strength and adhesive behavior at runnabilty condition at the fabricated corrugated fiber board [83] .

3.8.1 Grammage

The properties should be tested to decide the proper corrugated board application. Also, it is important to inspect the quality of the board to ensure that it functions properly in selected purpose. The term "grammage" refers to the weight of the paperboard per square meter, and it is typically expressed in g/m^2 at the testing protocol is ISO 536, Tappi T410 om-19 [82] .

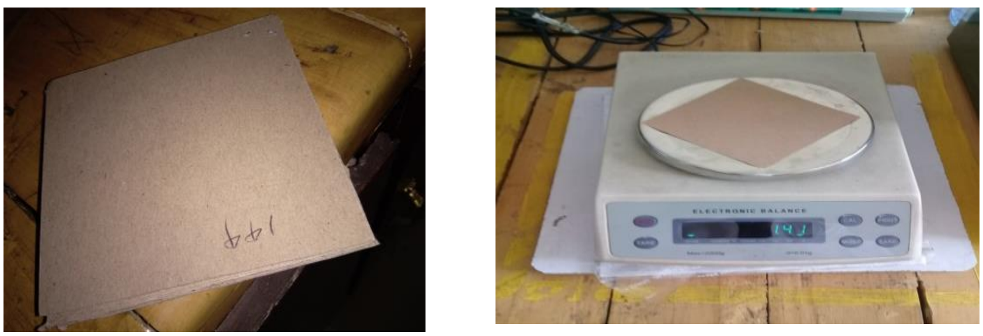


Figure 3. 2 Measuring paper grammage

3.8.2 Calliper

The calliper is referred to the thickness of the paperboard; wherein this report, the unit is expressed as millimetre for single paper at the standard testing method is ISO 534, Tappi 411 om-10 [81].

Figure 3. 3 :Measuring board and paper thicknesses.

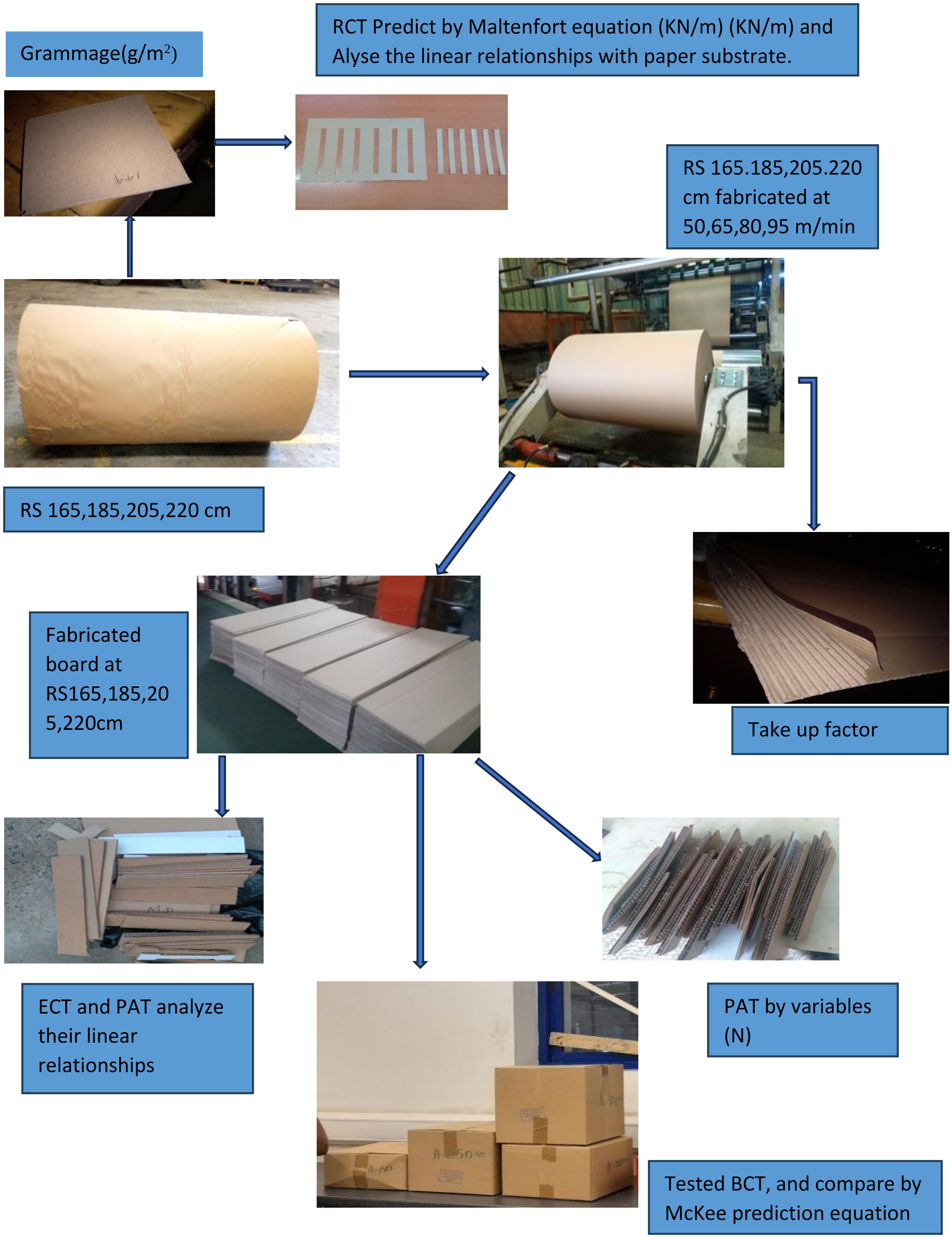
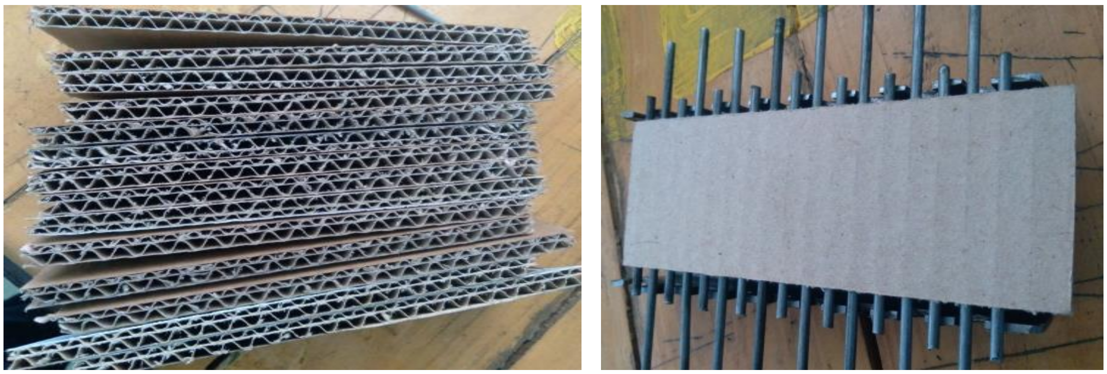


Figure 3. 4 :Experimental design

3.9 Pin Adhesive Test (Delamination)

Cut a minimum of ten test specimens from each test unit of a sample obtained in accordance with Tappi T 821 om-17 "Sampling and Accepting a Single Lot of Paper, Paperboard, Containerboard, or Related Product," taking an average of three samples from the middle and both sides of the board as follows. From firm, undamaged regions of corrugated board, "C" flute board measures 50 mm by 150 mm (2 in. by 6 in.) [84].

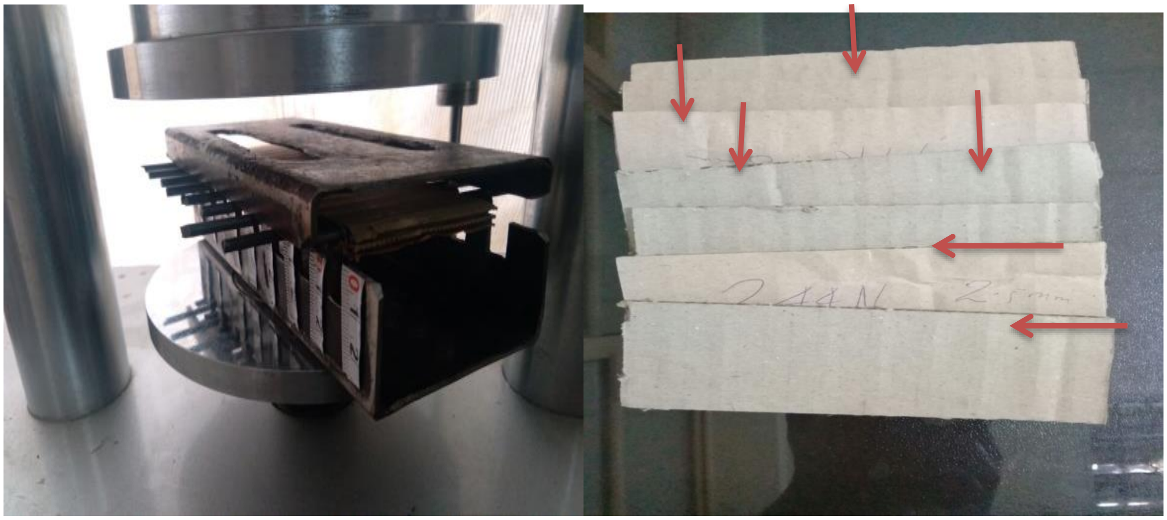


a) Material used for PAT b) specimen with fixture

Figure 3. 5 : Preparation of PAT, with specimen.

3.9.1 Pin Adhesive Test (Delamination) Procedure

To contact only the face that needs to be separated when the specimen is under load, place the pressure pins between the facing and the fluted medium. After that, place the support pins in between each pressure pin. Lastly, finish the test instrument's put and position it such that the designated facing for separation is downward and centered on the compression machine's platens (Fig. 3.6). [6]Apply a load with the compression machine at the Anti-pressure intensity tester (DC-YSY3000A) 2010 at a continuous rate of 12.5 mm per minute until the facing separates from the flute tips.



a) PAT with Delamination fixture. b) PAT board failure

Figure 3. 6 : Difference in PAT board failure under delamination force when using PAT test method.

3.10 The Edge Compression Test

During this project, ECT's of a number board combination were performed. The ECT results were used for box strength prediction using the McKee formula mentioned in Chapter 2. The ECT consists of subjecting a rectangular specimen to a load applied perpendicular to the flutes until failure occurs.

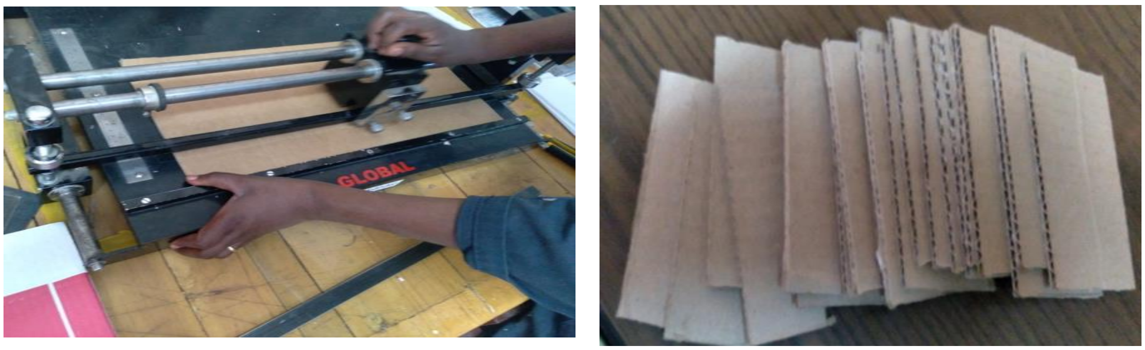
3.10.1 ECT Specimens

The dimensions of the specimens were100mm +0.5mm in the direction perpendicular to the flute by 25 mm + 0.5mm the flute direction Specimen was cut so that the width across the test piece did not vary more than 0.1 mm in accordance with ISO 3037:2013, FEFCO 2018 [85],[86] . This ensured that the loading edge was straight parallel and perpendicular to the surface of the board. In addition, the specimen had to be cleanly cut so that the flutes were not distorted and the edges of the specimen did not show any visible loose fibers or furriness the specimen taking procedure taking the average of three samples of the board, from the middle and both sides [49] .

3.10.2 The ECT Procedure

All specimens were conditioned and tested in standard temperature and atmospheric conditions in accordance with Tappi T 402 [80]. Prior to testing, the dimensions of the specimen were measured using a caliper. The ECT was carried out on a crush tester Anti-pressure intensity tester (DC-YSY3000A) 2010 and testomeric material testing machine as shown in figure 3.7 and figure 3.8 below. The tests were conducted at a crosshead speed of 12.5 mm/min in accordance with

FEFCO No. 08 and ISO 3037:2013. The specimen was placed between the guide blocks of the crush tester. A load was then applied perpendicular to the flutes until failure occurred [87]. The maximum load that the specimen sustained was then recorded. On completion of the test, the edge crush resistance was determined using Equation 3.6.1but on testomeric material testing machine the ECT result put in KN/m.



a) Specimen cutting   b) Material for ECT

Figure 3. 7:Preparation of specimen for ECT.

$R=F_{max}/L$ ……………………………………………………………3.6.1

Were

R=Edgewise crush resistance in KN/m

F_{max}=Maximum applied load in N.

L=Specimen length

a) ECT machine   b, failure under compression

Figure 3. 8 :ECT test specimen and testing machine and difference in ECT failure board when using ECT test method.

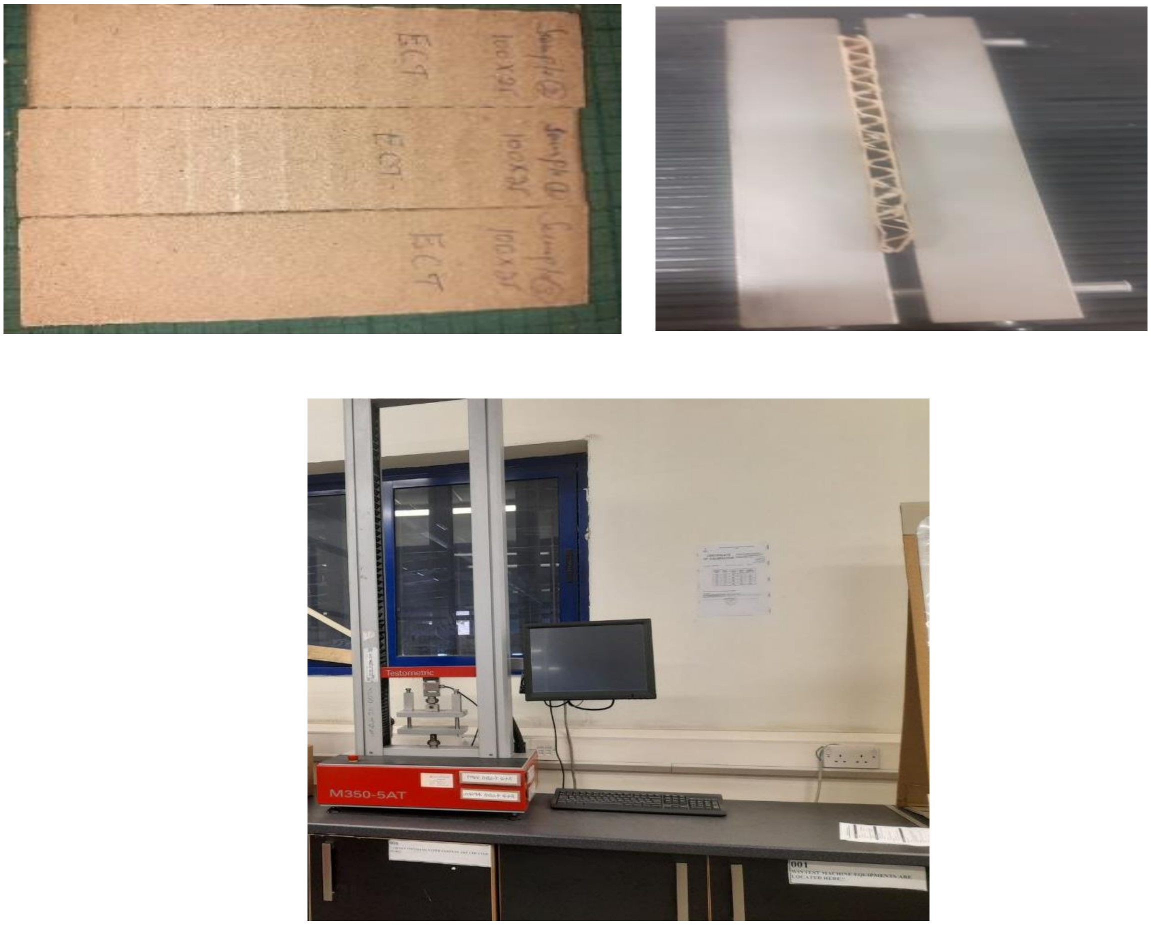


Figure 3. 9:Different heights of test specimen ECT testing machine failure board when using ECT test method.

3.11 Ring Crushes Test of Paper (RCT)

The corrugated Fiberboard products are subjected to crushing forces at ring crush tester GCCE -2010 machine. The edgewise compression strength aids in process management and gives a hint as to the expected level of compression resistance in the end product [88].

3.11.1 Specimens

Prepared 12.700 ± 0.025 mm (0.500 + 0.000 - 0.001 in.) wide, 152.4 ±0.200 mm (6.00 + 0.0–0.008 in.) specimens according to Tappi – T 822 om-02 using as the same as ECT procedure [89].

a) RC specimens

b) RC tester machine

Figure 3. 10: RCT, difference in paper failure under compression testing machine.

Along the reel size of the roll paper, the average value of the compression strength at CD direction of the minimum three the maximum four sample measurements is taken at the edge, center and edge.

3.12 RCT and Edgewise Compressive Strength

The ECT-Strength can be calculated from measurements of the compression strength of liners and fluting media. The accuracy of this calculation is directly dependent on accuracy with which the compression strengths can be determined and also on the accuracy with which the corrugated board's edge compression strength (ECT) is calculated.

Formulae:

$ECT = k\,(2\sum RCT_L + \alpha * RCT_F)$ ……………………..3.8.1

Where k= a constant α =the ratio of the length of fluting medium to the length of liner (the take-up factor).Theoretically k a dimensionless variable related to testing errors, testing method and manufacturing variables at the corrugated plant should always be equal to unity if there were no test errors if the liners and fluting media followed the same stress strain relationship and if the compression strength of the fluting medium was not reduced during the conurbation.

The edgewise strength of specimens with flutes vertical in combination with the top to bottom compressive strength of vertically fluted corrugated fiberboard shipping containers is related to the combined board. This technique can be used to compare different lots of similar combined boards' edgewise compressive strengths or to compare other material combinations.

$ECT=1.28*(RCT_1+ \alpha*RCT_F + RCT_2)$ …………………. 3.8.2

K_{RCT} depends up on measurement method=1.28±0.08, ECT is board edge crush determined by the FEFCO method [45] [69] .

3. 13 Box Compression Tests

BCT were carried out to measure the final corrugated board of the box. This value was then compared to the value predicted by the McKee formula as of experimental value. During testing the box is placed between two parallel loading plates as shown in the figure 11 and 14 Compressive load applied the top loading platen is attached to a flexible coupling which allows the platen to move according to the box deformation ensuring that a uniform load is distributed across the edge of the box [90].

3.13.1 BCT Specimens

The box compression test experimentally done in Addis Ababa institute of technology is 300 x 300 x 280mm corrugated box size for which five samples for RS220/50 and five sample for RS220/80 were tested by universal testing machine and the remaining 5 samples were tested by pressing different dead weights for more than two hour for RS220/50 fabricated in 50m/min(300*300*280) before printing by universal testing machine and (375*375*200) after printing of the each five samples were tested in burayu packaging and printing industry by using pressing of different dead wight applied and the others were computerized Electronic box compression test wereexperimentedat(300*300*150),(300*300*200),(300*300*250),(300*300*300),(300*300*350) of each 2of 10 samples for RS205/50 were examined and for five samples, and RS165/95 experimented at unlimited packaging industry in bishuftu,debreziet have tested in order to know the effects of box strength on the variables to determine the carrying capacity as well as the strength of the failure at the maximum deflection force of the corrugated box [91] .

3.13.2 BCT Procedure

BCT was tested according to Tappi standard T-804 0m-02.BCT was performed on across head of 12.5mm/min on FEFCO code 0201 [92] and [86] on universal tester machine in AAIT and unlimited packaging plc and pressing of different wight applied for the protocol to evaluate the effectiveness of the package method 1A Serious[93], [94] of the stacking load and compression at the static condition of dead cell in AAIT and burayu packaging and printing industry by keeping it for one hour and recording the incident on the box, it was possible to find out the strength of corrugated board, as displayed in figure 3.12.

a) The BCT of a corrugated box.

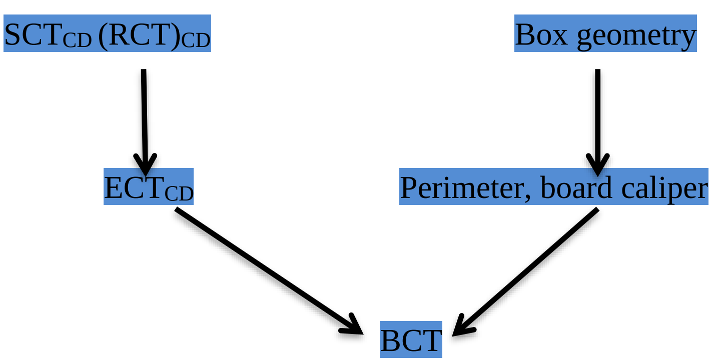
Figure 3. 11: BCT of universal testing machine at AAIT.

Figure 3. 12: BCT of weight dead testing.

Figure 3. 13: Samples of corrugated box at height of h=150/200/250/300/350mm.

Figure 3. 14: BCT of computerized electronic testing machine at unlimited packaging plc.

3.13.3 BCT of simplified McKee perdition formula



In this study, a verification of McKee formula and compare the compression strength was done experimentally by crushing different customer size corrugated boxes of from the case company at the variables of (Reel size, Speed and printing). The failure of the box has different as the effects of loading direction, perimeter, volume, and height [66].

The McKee formula has been widely used to predict the compression strength of corrugate boxes. The formula is defined as [90].

BCT = 5.876×ECT $\sqrt{p}$ *h………..3.10.1

Where BCT = Box compression test/strength (kg), ECT = Edge crush test (KN/m), P = box perimeter (m), and h = caliper (mm).

This is the most commonly used formula. However, its accuracy is acceptable only for the simplest boxes. The McKee formula should not be used if the length-to-width ratio or the height to length ratio of the box is too large [12].

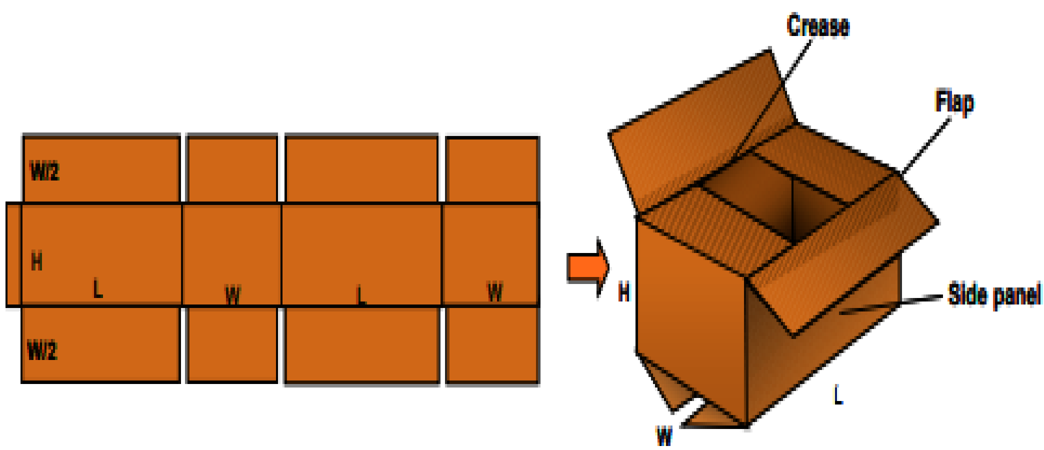


Figure 3. 15: Geometry of corrugated box a regular slotted container, code FEFCO 0201.

Size: Boxes are specified by their inside dimensions in the order of "Length" x "Width" x "Height." Length or Width dimensions shall be determined as applicable from the inside liner surface of the glue joint.

L (length) = longest direction of the box opening

W (width) = shortest direction of the box opening

H (height/depth) = direction perpendicular to the box opening [95].

3.14 Regression Analysis

A statistical approach called regression analysis contrasts a dependent variable with one or more independent variables. A linear model called linear regression can be used to assess whether two variables are statistically distinct [96] . ANOVA, on the other hand, is a statistical technique used to analyze unrelated groups to see if they share a common meaning.

To create a mathematical model that correlates board compression strengths [57] [45] and delamination strength test methods of the obtained mathematical relationships between ECT, PAT, RCT, paper and board properties have been clearly should consider the significant structural and component properties. These models may be utilized for thorough the strength and its effects for practical use. The plots of the PAT vs. ECT for reel size of 165,185,205 and 220 cm at speed of 50 m/min and 80m/min fabricated corrugated board, delamination Force (PAT) Vs. displacement, RCT vs. Corrugated paper thickness, RCT Vs. grammage, ECT vs. Board thickness, at standard conditions were subjected to several line-fit methods including the coefficients of determination using Microsoft Excel, Version 16 at one-way Anova. The line-fit methods included linear trend lines, for each trend line, an R^2 squared value was also generated were collected and compared.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

This chapter display the result obtained from the experiment and the calculation that were performed using the data from the laboratories at the case company, Addis Ababa institute of technology and unlimited packaging industry. Corrugated board, RCT, and paper physical characteristics sample results are shown Appendix A, B, C, D and E. The experimental results PAT, ECT, and BCT was tested at different runnability at the single facer profile of C- flute corrugated board determined their relationships by mathematical model discussed, analyzed due to the mechanical performance of the board and the fabricating process. On completion the average, regression analysis and the variance of the samples were determined. The errors on the bar in this chapter will represent the high and low values of the samples tested. ECT, PAT and BCT, while doing these experiments, thoroughly compared the effects of variables at RS165,185,205 and 220 cm at running speed of 50,65,80, and 95m/min on the fabrication of corrugated boards to verify the strength of the board. These values have different result on the final strength of the corrugated box during converting process according to the variables to use.

4 Experimental Result and discussion

4.1 Result and discussion on Pin Adhesive Test (Delamination Testing)

The goal of the corrugator bonding technique is to produce a reliable, durable bond that will improve the quality., and provide a more consistent mechanical board performance. The corrugator board delamination strength is affected by the bonding process since the fabricator speed (50,65,80,95m/min) is governed by the rate of adhesive tack and the rate of bond strength development, under the reel size of 165,185,205,220 cm. An optimal matrix of working parameters, including speeds and reel size, results in the bonding. The mechanical alignment of the corrugating and adhesive applicator rolls mechanisms, as well as the properties of the adhesive formulation, are also crucial. By taking into account the corrugating process guiding principles, the corrugated bonding, and its effects on the performance of corrugated boxes, one may learn how all these variables and parameters are connected and the experimental analysis has been done to determine the effects of the variables speed and reel size.

Fig. 4.1.1 shows the results, of RS165cm and RS185cm have more resistance force to separate the board than others. RS205cm, RS220cm, were fabricated at a speed of 80m/min need less force was used to separate the board, Similarly, when RS165,RS185,205,220 cm is fabricated at speed of 50 m/min, it has more resistance strength to delaminate the board, based on the average results at appendix A,table1.1, RS 165cm at 65m/min fabricated board, as reference to compare others accordingly RS185 cm by 1.4%, RS 205 cm by 2.48%, and RS 220 cm by 5 % are reduced. This means their strength is less because of Paper breakdown due to shear strain is frequently accompanied with bending force that results in delamination. The process of creating flutes involves both tensile and bending forces.

RS220 cm is fabricated by 50 m/min and RS165/50 strong force needs to delaminate the one of the three layers compare to by its own reels size during increment of the fabricated speed. To see here is that take the same real size 220cm at the speed of 65 m/min it shows a difference of 5 % between the two fabricated boards to delaminate the board of the pin adhesive strength. The average value of the pin adhesive test strength of the force result expressed at newton, and at 80 m/min running speed of those fabricated by the RS 165cm as reference, RS185/ 205/220 cm, shows a difference of 4.16%, 10.29% and 13.25% are reduced respectively.

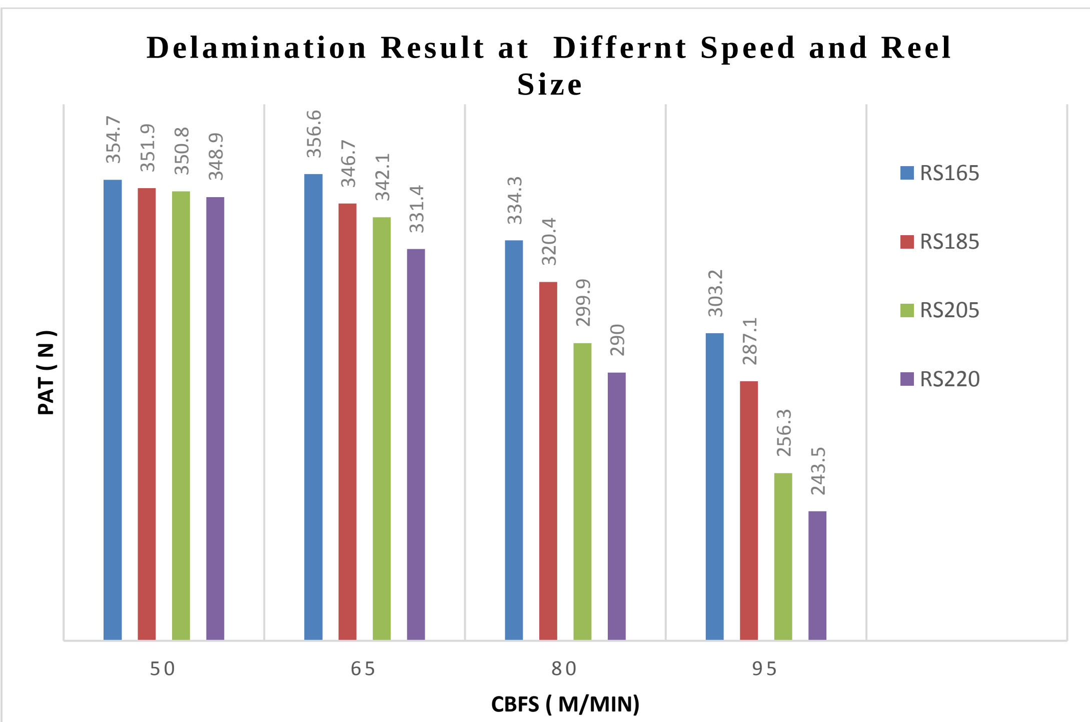


Figure 4.1. 1: The PAT with an error bar indicating the minimum and maximum values of the sample results of RS165,185,205 and 220 at fabricated speed of 50,65,80 and 95m/min.

To confirm this, RS165, 185, 205 and 220 cm reel size were tested the samples of fabricated corrugated fiber board at the 95 m/min running speed, their results show the strength varies to delaminate the CFB or the force to separate the board, RS165 has strong strength at both conditions compare to RS185,205 &220 cm fabricated at 50m/min. RS185 by 23%, 26.75%, 29.85 % and RS185/95 reduced by 10.15%. The same properties of the material at different length of paper as reference of 220 cm reel size ,55cm from 165-reel size, 35 cm from reel size of 185, 15 cm from reel size of 205cm. The hardest and the weakest bonds are created when running at 50,65,80 then 95 m/min at both liners, or the medium fluting fails, and the uniqueness of this paper difference weakest pin adhesion values are produced. The converting process investigated how the characteristics of the corrugated board were impacted by variations in glue quantity at the reel size and the speed.

Table 4.1. 1: Experimental result of delamination testing at printing variables.

variables	Average PAT(N)	% Difference
RS165/80	341.1	Ref
RS165/80/5	310.5	-8.97
RS 185/80	323.4	Ref
RS 185/80/5	288.9	-10.667
RS 205/80	303.4	Ref
RS205/80/5	262.9	-13.35
RS220/80	297.9	Ref
RS 220/80/5	246	-17.4

Table 4.1.1 at appendix A table 1.2, 1.3 and figure 4.1.2 average value shows the delamination of the printed board of the PAT fabricated as a reference of RS165,185,205,220 cm by 80m/min, after printing their value reduced by is 8.97,10.7,13.35/17.4% respectively and RS220 cm less resistance delamination force that is required to separate the test liners from the fluting. The value indicated that the CFB need to delaminate the less force means the CFB mechanical performance of the box will less because of the fiber board has sandwich structure one of the three paper not laminated well the strength of the board are reduced then the load distribution on the box wrinkles

initiated and failures propagated at the weakest strength of the perimeter of the box at the load-deformation reactions of the failures in Figure 3.16 are shown.

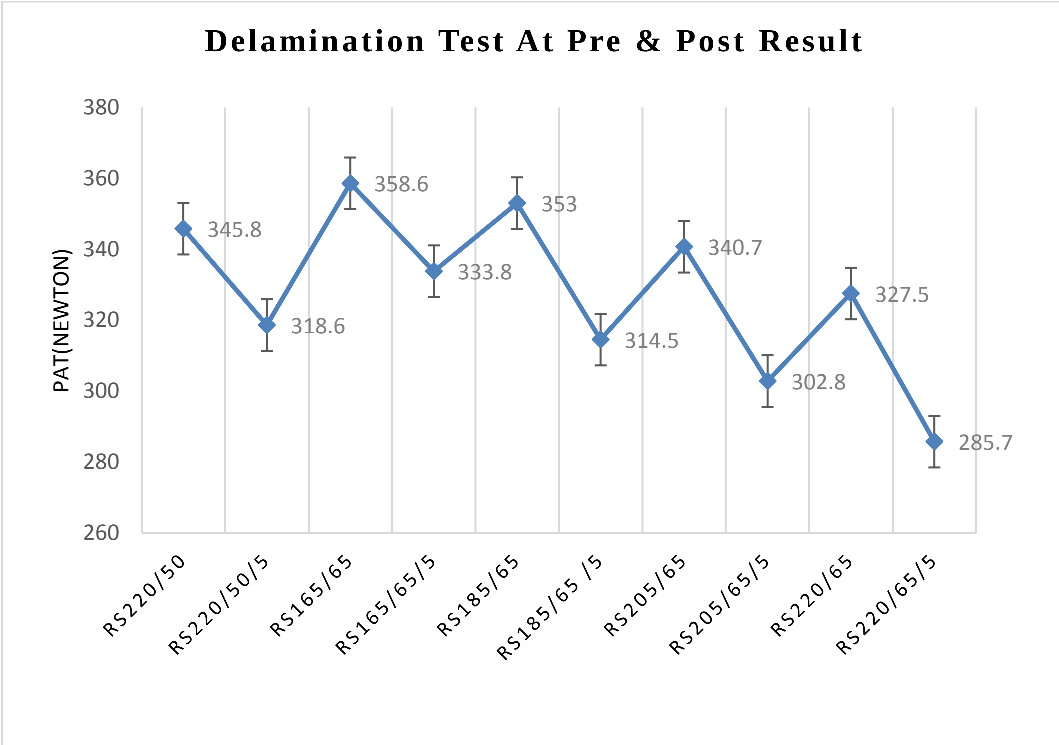


Figure 4.1. 2: PAT results show the mean load with an error bar reflecting the sample test's minimum and maximum values.

The strength of the corrugated board is different value before and after printing is respect to the reel size and the speed at which the board is fabricated. RS220 cm fabricated at 50 m/min and RS165 cm at 65 m/min, RS220 cm fabricated at 65 m/min is 12.76 % less, while the RS220 cm at 65 m/min with the same reel size and the same printer has a production speed, was 7.86 % less than the RS 220 cm fabricated by 50 m/min at figure 4.1.2 clearly shows their value before and after printing of the pin adhesive strength. In order to compare the results obtained by the reference of the sample fabricated by RS165 cm before printing, the PAT result reduced by 6.9% the strength vary from converting to printing. RS220/50 from 345.8 to 318.6 reduced by 7.86%, RS165/65 from 358.6 to333.8 by 7.86%, RS185/65from 353 to 314.5 by 10.9%, RS205/65 from 340.7to 302.8 by 11.12% and RS220/65 from 327.5 to 285.7 by 12.76%. The corrugated fiber board is then damaged throughout the conversion to printing process, during which it is slit, scored, printed, slotted, and folded; however, most of this damage is done on purpose to satisfy the needs of the finished box.

Table.4.1.2 at appendix A table 1.4 the variable of RS165,185,205,220 cm at the fabricated speed of 95m/min the stronger force has the more deflection or displacement need to separate the liners from fluting during loading load on the box can fail easily. More delamination happened, as shown at chapter two paragraph 2.11 at the condition of the failure bonding separation of the corrugated board, because glue skips are present or some of the weaker bonds are unable to withstand the stresses applied as well as during printing.

Table 4.1. 2: Experimental result of delamination testing at printing variables.

Variable	Force(N)	Displacement (mm)
RS165/95	308.7	5.14
RS185/95	288.8	4.85
RS205/95	273.4	4.48
RS220/95	260.8	4.23

The strength of the cured bond and the green bond are both adversely affected by faster corrugator speeds. The speed effect seems to be related to both increased mechanical stress on the green-bond and decreased adhesive transfer to the medium flute tip. The larger the reel size, fabricated at 95m/min the less force the board will likely to the more delaminate, which is related to the strength of the board. This situation also makes the board more delaminate during creasing and folding, making its strength less.

The force necessary to separate corrugated board between the flute points of the corrugated medium and its liner board facings is calculated using this method. To produce corrugated boxes of good quality, the corrugated medium must adhere well to its facings. The pin adhesion test gives a way to assess the type and strength of the connection created during the combining process and may be used to identify specific manufacturing defects, such as inadequate adhesive penetration, patchy adhesion, and container board with a weak internal bond.

4.2 Result and discussion on ECT & Paper properties

The correlations of the compression properties of the board and paper under variables of the reel size, and its fabricating speed condition. The factor influencing the box strength is the corrugated board's edgewise compression strength. It is possible to extend this interlink relationship to the crucial strength characteristics of paper substrates. So, this will enable the paper to make corrugated board with the required compression strength to provide a desired board strength for optimum runnabilty circumstances by choosing suitable manufacturing process with specific strength and paper substrates.RS165,185,205 and 220 cm by taking the samples of corrugated board to measure the ECT, and RCT were made directly use the experimental results obtained from the corrugated board fabricating at the speed of 95,80,65 and 50 m/min at appendix B from table1.1up to 1.6 so as to predict the box strength of the McKee formula (box strength predicting formula). The reel size corresponding with the working speed, the experimental and theoretical results are set. It is clearly shown which one has more strength of the corrugated board at the aforementioned variables.

Figure 4.2.1 demonstrates the effect of the running speed at which the manufacturing of CFB on the medium and liners crack and wrinkling defect on the ECT of the combined board has occurred at variety of places on the samples after tested. The converted boards were compared according to their ECT results showed that the one at RS165-RS220 cm at 50 m/min was stronger compression strength than the others such as RS165 - RS220 cm, 65-95 m/min. As a starting point, by making a reference to this results, RS 185 & RS205 cm at 50 m/min the strength reduced by 4.49%, 5.15 %. RS165cm at 65 m/min it has more strength than others, RS185 by 2.54%, RS205 by 10.4%, RS220 by 13.82 %, was reduced. RS165 has more compression strength of the reel size at 80 m/min, RS185 by 4.37%, RS205cm by 12.86%, RS220cm by19.56% strength is reduced. The measurement of compression strength represented by the data as shown in figure 4.2.1 RS165/65/80/95 the compression strength of the board is reduced by 4.63,9.94,13.02,22.67%. RS185/65/80/95by8.62.8,9.86,16.83,23.71%,RS205/65/80/95,by9.91,17.26,25.66%, RS220/65/80/95 reduced their ECT value by 19.94.5/27.29/32.89%, RS165 and 185 cm fabricated by 95 m/min, it is to show the strength that can be reduced but the board fabricated above 80 m/min both reel size 205 and 220 has various strength and breaking problems at a high level this will lead to defect CFB.

The material has various mechanical properties along the mutually perpendicular directions due to the fibers produced during the board production process, which have the same physical characteristics regardless of direction, they exhibited different compression strength indicated in figure 4.2.1.

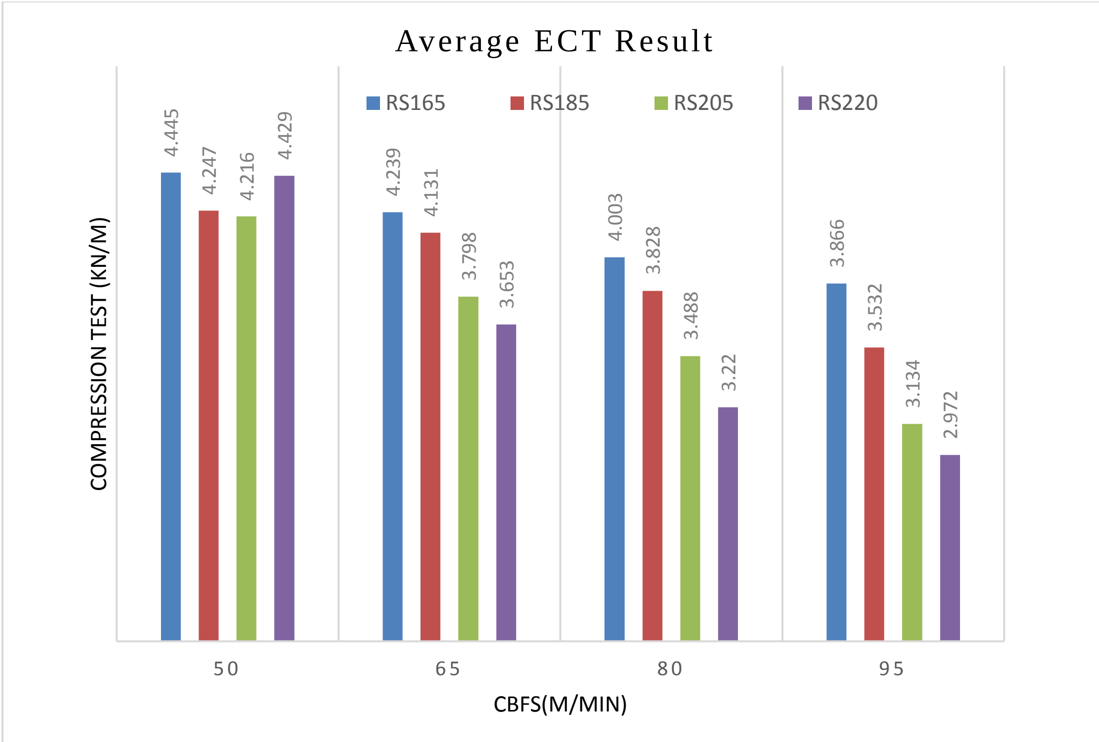


Figure 4.2. 1: Average ECT, RS165, 185,205,220cm at CBFS of 50, 65, 80, & 95 m/min.

Fig.4.2.2, the results of ECT indicate that the board using the variables (number of printing homes) has impacts on the strength of the board, this is confirmed by the results of the ECT, which shows that the samples printed at five colors machine from 12.33-14.66% are degradation of the compressive strength because of the high-low flutes, the hygroscopic effect of paper, and associated factors described at chapter two paragraph,2.5,2.7and 2.1.14. To compare the effect of printing on the crush strength of the corrugated board on RS165 at 80 m/min & RS220 at 50m/min on the 5-unit printing machine, the compressive strength of the data show at appendix B table 1.3 that there is difference in the ECT of RS220/50/ 5 reduced by 12.33 % at the same time RS165/80/5 the strength is reduced by 14.66% factors of decreasing the performance of ECT are, mechano-rheological properties of paperboards (grammage, density, porosity, strength, elongation).

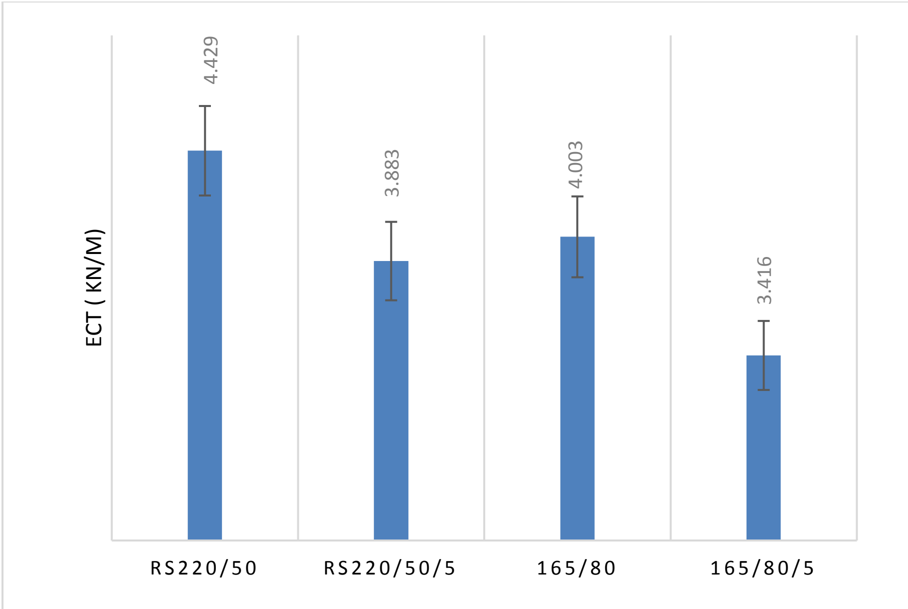


Figure 4.2. 2: Bar plots average ECT result of minimum and maximum tested sample.

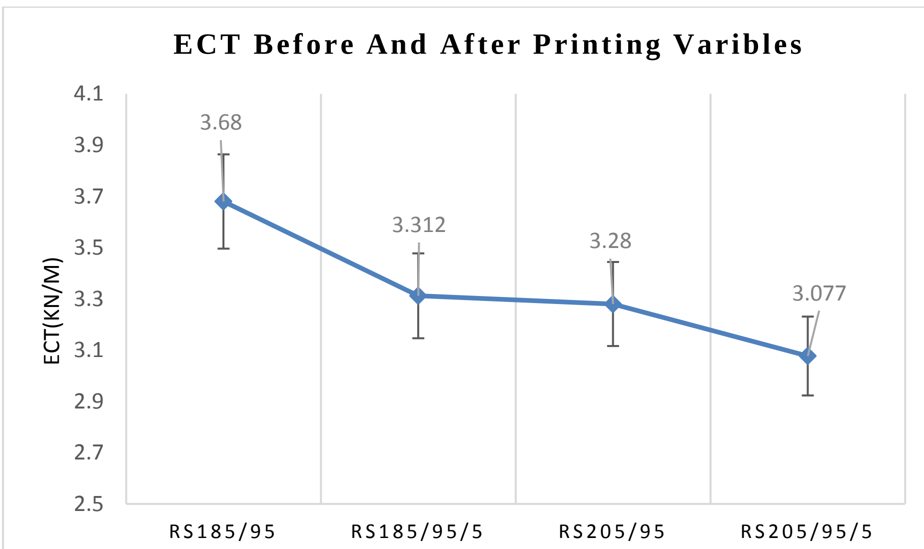


Figure 4.2. 3: Maximum and minimum standard error of ECT result of printing variable.

At the same time after printing the compression strength reduced from RS185 to RS185/95/5 by 10% and from RS205/95 to RS205/95/5 by 6.18% at figure 4.2.3.

The following method was used to calculate the theoretical ECT of the real RCT for corrugated boards in the form appropriate for three wall board:

$ECT = K (RCT_1 + RCT_2 + \alpha F)$ Where k= a constant α =the ratio of the length of fluting medium to the length of liner (the take-up factor) $\alpha = 1.25$ for C-flute single facer corrugated machine.

Theoretical ECT=K (RCT1 +RCT2 +αF) ……K=1.28 ± 0.08 In order to determine the theoretical ECT and the measured RCT in the Maltenfort model, the RCT with the predicted ECT, using the paper components of the combined compression strengths. The Maltenfort equation obtained as varies as per the reel size and the speed to fabricate the corrugated board, using all data generated the ECT before converting and after converting conditions plotted at figure 4.2.1 and the outcomes are at table 4.2.3. In order to do the calculations for the board, the RCT paper substrate findings and the actual ECT result of RS165-220 fabricated boards' samples. The design of these equations makes it abundantly evident how important various material characteristics are to the combined board's box performance, which plays a major part in determining box strength. The complicated corrugated board structure's inherent material strength is attempted to be quantified by measuring ECT. the average value of actual ECT results obtained after exposure to converting process at different speed of manufacturing conditions.

If this method is based on appropriate statistical weighting factors, it provides good predictive accuracy of the performance of the combined strength of the board through process optimization of the corrugated fabrication. At chapter two paragraph 2.13 according to Maltenfort equation the paper compression strength test methods that are used, as well as the influence of fabricating factors at the corrugated process, it clearly shows the different paper properties, the strength level of the product to identify and predict the final board performance. According to the results obtained in the laboratory and the theoretical ECT of the Maltenfort equation, **the paper to compression strength is 3.6KN/m.**

The board's ECT increasing and decreasing the compression strength at different fabricated speeds at varying Reel size settings for the same paper substrate, however, the cumulative effect of the various component strength reductions. Nonetheless, the board's ECT reflected the overall impact of its parts at both a slight reduction and an increase at high value. It was hypothesized that the various paper grades and their finishing makeup may have some bearing on the variation in strength decrease during conversion. The important part of any particular sized box of the ECT, which is an indicator of the basis weights and the quality of the components and whether or not there is enough strength on the corrugated board. ECT certainly made a lot more sense as a specifier of strength performance especially after the development of fabricated board liners. The models proposed of ECT vs paper qualities and most of them suggest that ECT based on different variables.

Table 4.2. 1: Measured RCT with calculated and compare to theoretical ECT.

Variables	Average ECT (kN/m)	Theoretical value (3.6KN/m)	Value %
Reel size 165/50	4.445	>	18.74
Reel size 165/65	4.239	>	14.79
Reel size 165/80	4.003	>	9.77
Reel size 165/95	3.726	>	3.06
Reel size 185/50	4.247	>	14.96
Reel size 185/65	3.881	>	6.94
Reel size 185/80	**3.528**	<	**-2.37**
Reel size 185/95	**3.132**	<	**-15.32**
Reel size 205/50	4.216	>	14.33
Reel size 205/65	3.798	>	4.90
Reel size 205/80	**3.288**	<	**-9.85**
Reel size 205/95	**2.963**	<	**-21.89**
Reel size 220/50	4.429	>	18.45
Reel size 220/65	3.653	=	1.13
Reel size 220/80	**3.02**	<	**-19.6**
Reel size 220/95	**2.872**	<	**-25.76**

Using the model, it shows the strength and quality of paper use as well as its ability to withstand the various pressures it faces during converting process. Using the measured RCT, from theoretical ECT, RS165cm fabricated at 50-95m/min, are higher crushing strength from 3-19%.RS 185cm fabricated at 50-80 m/min at combined of the crushing strength are from 7-15% higher than the theoretical ECT. RS205 cm fabricated at 50-65m/min from 5-14% and RS220cm fabricated at 50-65 m/min 1-18% more than theoretical ECT strength has been observed and it helps to monitor the strength and production condition that can be achieved during fabricating. In the highlight, RS

185,205,220cm shows 10-26% reduction in strength from theoretical ECT when fabricating at 80-95 m/min. By comparing the results of the two methods of the measured RCT with theoretical ECT, it will be possible to identify which variable is the best strength or weakness for the packaging function and purpose from material quality management during fabricating process. These models can be used for detailed to know the strength and its effects for practical use and runnabilty condition at the fabricating CFB variables.

Figure 4.2.4 compared the effects on ECT board samples heights at 25, 30,40,50, and 60, the data show at appendix B table 1.4 and 1.5 that there is discrepancies in the crush strength at measured height 1.14,5,19,24% are reduced the compression strength of the board, observation of the result at shorter height of the ECT value are higher at 25 and 30mm fabricated by RS205/50. The comparison of compression strength with as height increases, the strength decreases. This means as the height of the box increases, the strength of the corrugated box decreases. During carrying of the corrugated box fail or collapsed and the property inside will be broken or damaged. RS205/80 shows a decrease of 1.14 %, while 40mm height is 5.08%, 50mm height is 19%, and 60mm height is 24.33% degradation of the strength has been shown.

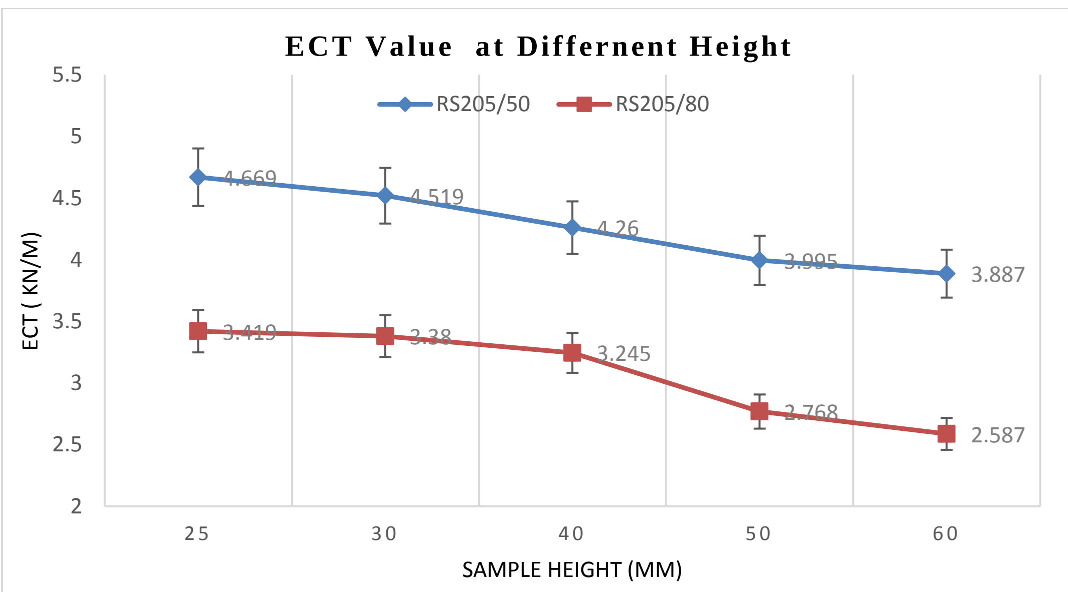


Figure 4.2. 4 : The ECT value RS205 at 50 and 80 m/min at 25, 30, 40,50,60 mm height.

Figure 4.2.5 the compression results of the samples of fabricated corrugated boards at RS220/50, RS165/65,RS185/80,RS185/95,RS205/95, RS220/95, the variables are measured by computerized electronic ECT testing machine show that the average results of the variables are showed on table

4.2.4 and appendix B, table 1.6 As described in chapter two a 10 % change in the compression strength 7.5 % change in the corrugated board weather reduction or improvements on the structural strength of the combined board. Edge crush resistance may reduce package performance according to the findings, for RS205/50 and RS205/80 16.7-24.32 % reduction in edge crush resistance was observed at the height of the sample increased from 5-35mm at both variables of the same fabricated condition.

The higher compression strength of the ECT value of the corrugated is seen in less millimeter in deflection except RS165/65 but the others with less compression strength shows increased the displacement of the board in millimeter, which is in line with stiffness of the mechanical characteristics of the corrugated board except at reel size 165 cm at all condition of the mechanical performance testing result was higher than others variables depend on the high/low effect and the flexural properties indicated at chapter two paragraph 2.10.1,2.11 and 2.12. Table 4.2.2 and appendix 1, the higher the compression value the less corrugated board displaced but this condition is not always true because reel size 165 cm fabricated at 65 m/min the displacement of the corrugated board is less than the reel size 220 cm fabricated

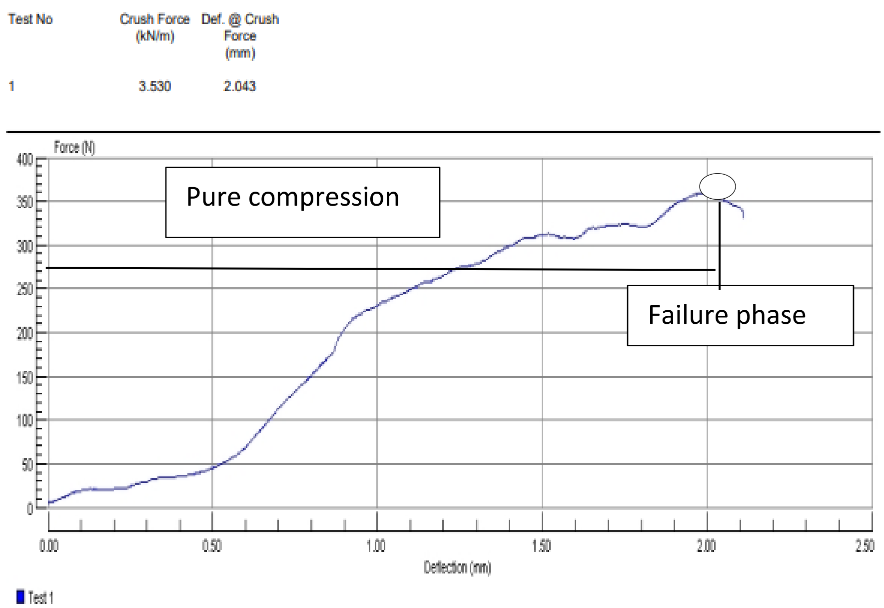


Figure 4.2. 5 : Failure chartcerstics of ECT value

result was recorded. The obtained value has a direct and effect on the final strength of the corrugated box on the flexural stiffness as well as the mechanical structural of the board fractur

Table 4.2. 2: Average ECT result with deflection at crush force.

variables	Average ECT (KN/m)	Deflection at crush force (mm)
ECTat RS220/50	4.7575	0.7131
ECTat RS165/65	4.3347	0.6479
ECTat RS185/80	3.969	1.2232
ECTat RS185/95	3.6177	1.5458
ECTat RS205/95	3.0661	1.9208
ECTat RS220/95	3.012	1.9337

by 50m/min due the structural of the corrugated board. In the ECT test, the components won't reach their maximum strength simultaneously if they do so at deflections that are noticeably different from one another of the measured ECT will be higher and lower in this case. This idea of how variations in the load deflection properties of linerboard and medium affect ECT it is expecting to that of a box as stated in chapter two paragraph 2. 10.

4.3 Result and Discussion on BCT Performance of CFB

The experimental testing can be done on packages to assess their performance in terms of strength. For instance, a box compression test is frequently used to assess the stacking performance (BCT). This test yields the box compression strength, or the greatest force a box can support before failing, as described by the BCT-value. The CFB strength of the McKee formula can be primarily characterized by the cross-machine (CD) direction and edge crush test (ECT) performance as well as the perimeter of the CFB box and board caliper. The mechanical characteristics of the board can be ascertained through material characterization and fabricating process.

Table 4.3.1 the box strength prediction using the McKee formula at the reel size of from RS165-220 cm at the speed of 50, 65,80,95m/min of fabricated corrugated board on the box compression strength of the predicted value tell us the information of how much the box strength to carrying capacity theoretically. The ECT is important mechanical strength performance criteria for CFB.The ECT can be measured in CD, Since the flutes in the test specimen are oriented vertically according to appendix B table 1.1, the corrugating media directly contributes to the compressive strength of the corrugated board.

Table 4.3. 1: Calculated McKee box prediction.

CBFS(m/min)	RS165 (kg)	RS185 (Kg)	RS205 (Kg)	RS220 (Kg)
50	184	176	175	184
65	176	171	157	151.5
80	166	159	145	133.5
95	160	146	130	123

RS 165 and RS 220 have the same compression box strength, while RS185 and RS205 show similar results, which are 5% lower. Compared to the RS165/65 the board produced at production speed was for 165-reel size, followed by 185, 205 and 220 which reduced the strength by 2.84, 10.79 and 13.92% respectively. RS165,185, RS205,220 fabricated by 80m/min reduced the strength by 4.21,12.65 and 19.57 % compared to 165/80 respectively.

At 95 m/min, RS165 is the first, and the rest of RS185 is followed by 205 and 220cm, which have reduced strength by 8.75, 18.75 and 23.125 %. The severity of high/low flutes worsens, corrugator speed increases, and corrugator bond strength decreases, the ECT decreases. RS165cm at 50, 65, 80, and 95 m/min decreased by 12, 16.6, and 20.6 %. Also, RS185cm at 50,65,80,95 m/min decreased by 13, 17, 26, 36 % respectively. Compared to RS205cm at 50,65,80,95 m/min, reductions were seen by 14, 22.3, 30 %. RS220cm at 50,65,80,95 m/min 18, 32, 39.7 % of the compression box strength was reduced. This means that load distribution does not differentially influence "inside" and "outside" as long as both linerboards have the same paper substrate. The liners and the fluting within the box will be able to withstand a higher compression load than it would have if the construction had been symmetrical and the lighter or less rigid linerboard had been in that location as stated at chapter two paragraph 2.12.2.

It can be understood from the experiment that it is possible to predict the strength of board by using the actual result obtained by considering correction and factor safety to find out the carrying capacity close to the actual box and identify the variables to make the optimum runnability. at fig 4.3.1 showed that two tests were experimented at the same reel size and the same corrugating speed of CFB, at the box dimension of (300*300*280) & (272*180*180) mm box.RS220cm at 50 m/min as reference to compare 14.28% reduction of the compressive force.

Of course, even though they have different sizes, after printing, the bearing strength of the box strength is reduced by the specified amount according to the experiment. RS220 cm at 50 m/min after printing by using dead weight method for stayed more than two hour and thirty minutes at customer size box of the actual weight approximately 96kg, here is the box compression strength before and after printing is different the main thing is to show the experimental outcome, effects of each process in to consideration of the variables to reduce the compression strength of the final mechanical strength of the box.

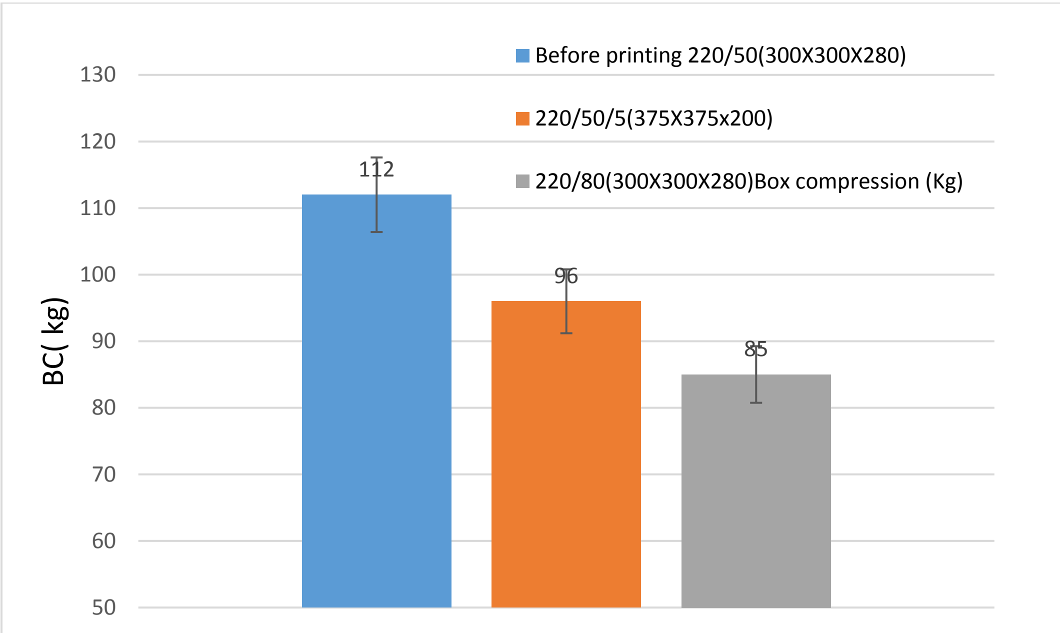


Figure 4.3. 1: The bar error indicates the maximum and the minimum of Actual Box compression test before and after printing.

Figure 4.3.2 In this experiment, five size boxes were used, the set consisted at the box dimension of (300*300*150), (300*300*200), (300*300*250), (300*300*300) and (300*300*350) mm box. At different height the data for this test was presented in Appendix C table 3. 2, regarding to the effects of height, as reference, the box strengths were reduced by 14.8/37.06/54.69 and 45.16% was recorded. This shows that the higher the height of the box, the more deformation will be occurring at the box. The Strength decrease of boxes due to an unintentional crushing during material converting. The result demonstrated that the maximum load bearing ability of the corrugated board box will therefore depend on the height and also to a great extent on the ability of the corrugated board to resist buckling of the box panels respect to box dimension. Both the box size and the converting process can influence the relationship between the calculated and the measured BCT. When boxes of different size are made up of the same board has different BCT value. When there is a difference between length and width, the longer side tends to bend out and the shorter side tends to bend in when the box is crushed. The linerboard's and fluting sizable impact on the box compression stiffness term is responsible for this outcome. It has been demonstrated that the ECT is influenced by the linerboard and medium's compressive strength in the cross-machine direction as well as the quality of the box plant converting procedures.

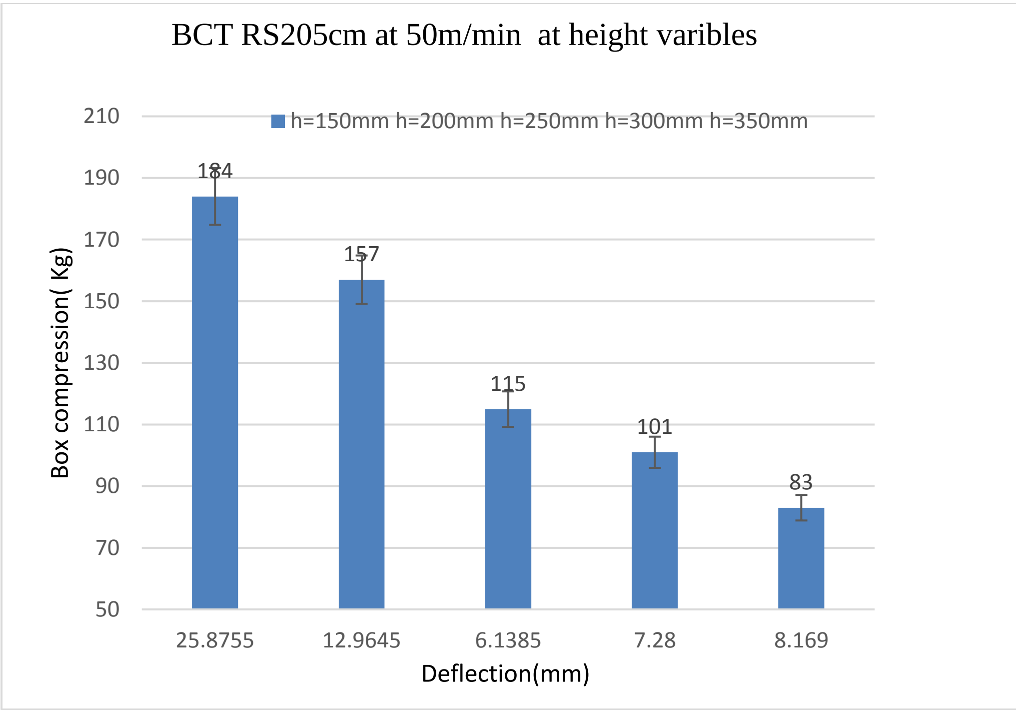


Figure 4.3. 2: The BCT result at height variables present the mean load with an error bar indicating the minimum and maximum values of the test set.

Box compression strength will be decreased if there is a significant loss of ECT as a result of the converting. As shown in Table 4.3.3, different results were recorded, the smallest height but the same base the compression strength of the box 184.09 kg at the failure deflection at 25.8755mm followed by the height of 200 at 156.7 kg at 12.9645 mm. Their height is 250/300/350, their compression strength 115/100/83 kg, and 6.13/7.28 8.16 mm deflect or fail the box. This does not mean that the failure deflection of a stronger board is greater, because if it had better strength, the failure deflection would be smaller at height of 250mm at chapter two paragraph 2.6.2 and 2.12.1 according to the experimental finding of table 4.3.2 the same reel size fabricated speed and base dimension at figure 4.3.3. The CD edgewise compressive strength of the components and, consequently, the height of the box and the same base dimension, are the determinants of combined board ECT. Yet in the maximum height column test, the compressive characteristics of the components are play and impacted differently by height, buckling of the flute pieces is possible. Although the component elements buckle and the poor bonding is thought to represent the layered structure of paper or board, the analysis revealed that increasing the component box heights can be predicted to reduce the aggregate board of the pure compression strength.

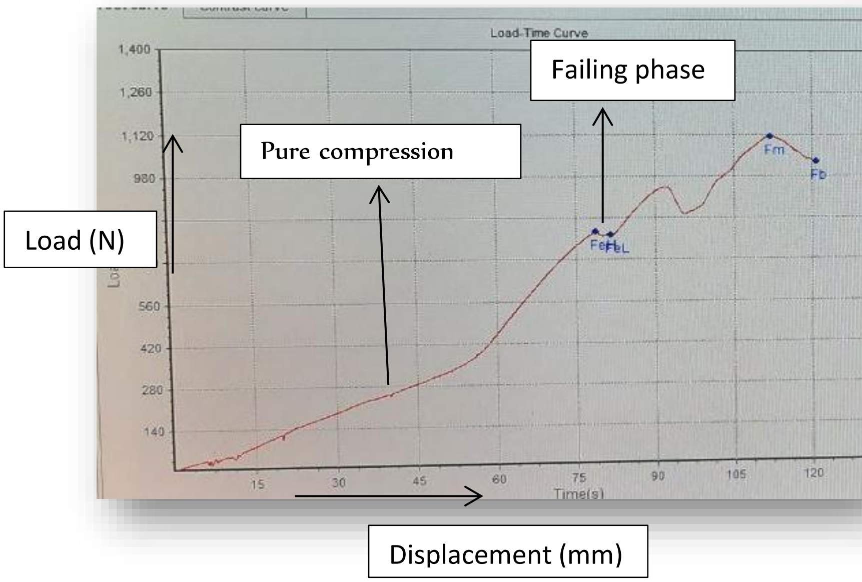


Figure 4.3. 3: corrugated board boxes' load-deformation response during compression.

Figure 4.3.3 Understanding the function of the package is crucial when analyzing the results of a BCT test in order to correctly determine which load was measured and is pertinent to the particular box dimension and inside the box containing function. The BCT is frequently seen as the initial point of collapse, where considerable buckling and a loss of structural integrity occur. However, some boxes, especially those with more complex structures, can experience multiple peaks and valleys before reaching the point of maximum load. This is especially true for boxes with more complex structures. Many load-deflection curves experience the maximum load where the box begins to appear damaged, with decreasing load support as the box collapses.

Table 4.3.2 the ECT value on packed box and its center-rounded strength were related to the bending property, which shows different failures of the compression of the packed board with consequences on the board region due to the factors of signal various failure characteristics. Differences can be observed between various aspects such as peak load compression displacement, fracture/collapse location and shape of the product line. The strength and characteristics of the box produced at different production speeds, when analyzing the average BCT value with deflection at first collapse (mm) of the board boxes made, RS220 and RS165 at 50m/min the pure compression strength 112 kg and 114kg fail at 20.922mmand 9mmrespectively. RS165/95 at 81kg 16.909 mm, RS185/95 at 61kg 2.403 mm in an actual box until failure and how it affects the failure behavior varies depending on the basic assumption this result directly connected to the edge crush test result at appendix B table 1.6.

Table 4.3. 2: average results of different BCT.

Variables	BCT (N)	BCT (Kg)	deflection (mm)
RS220/50(300*300*280)	1096.2	112	20.902
RS165/50(300*300*280)	1118.8	114	9
RS220/80(300*300*280)	752.3	85	16.902
RS165/95(300*300*280)	748.95	81	14.128

This test can be used to evaluate boxes that are empty, in the test, the box is compressed until it ruptures, the flute formation criterion includes two subcategories: Fractured Flutes and High/Low Flutes. Both of these defect categories are influenced by the medium physical properties and attributes, and by the corrugating process variables' compressive force of corrugated board boxes is measured at stronger board practices tend to have a greater impact on deformation, while smaller ones deflect faster. But RS165/50 the maximum load 114 kg and the deflection at maximum value at 9mm are recorded. Damage to the structure of the flute will weaken the performance of the board which provides the opportunity to understand and measure the performance through the morphological changes of the flute.

RS165,185,205,220 cm at a fabricated speed of 50m/min are higher compression strength according to this the box size of actual compression test 300*300*280 an average value of 112 kg after printing another customer size 375*375*200 has average value of 96 kg before printing and after printing the strength degraded by 14.28%. During the fabricating process through to the end use, such as crushing of flute due unwanted damages to the profile that may happen anywhere. This damage will weaken the stiffness properties of the board and allows failure to propagate quickly from the localized failure area on the board.

By simple mathematical expression of using at the McKee formula the ECT value of corrugated board and box dimension will help to predict the actual corrugated box strength as well as using the factor of safety to determine the carrying capacity of box compression and the stacking strength. ECT have different compression strength results to complement and complete the McKee box prediction and to make it useful for comparison at the theoretical and actual results, in this case the shortest heights (300*300*250) and the box size (300*300*300) not taken because of it violated the McKee rules. Different variable during the fabricated board the failure behavior is depend on the physical properties underlined at chapter two paragraph 2.12.2 as well as the manufacturing procedure. Based on the equation at 3.10.1 at table 4.3.1 the box prediction result has been displayed. The difference between the obtained theoretical result and the actual one is shown in the table 4.3.6. This deference of the compression strength is losses especially at recycled paper drops tensile properties and the strength of the paper loss because of reducing the elastic module and tensile strength, due to, properties of paper, corrugating size, machine condition, fabricating speed has effects made a difference in the results.

To determine the effect printing variable in consideration during box prediction examined and discussed the variables influencing the preservation of compressive strength during fluting, or the effect of the fluting process on the findings, the fluting procedure causes corrugated board to lose 15–20% of its ECT potential and 14.28% on the box. This happens as a result of the fluting process, which under the forming conditions significantly reduces the medium's and both liners of the edgewise compressive strength. The nature of the failure and the strength of the compression complement each other; That is, the failure behavior can explain the compressive strength and vice versa. Therefore, analysis of failure behavior is considered as an effective approach to explain the compressive strength of corrugated boxes. Box compression failure lies between the pure compression and the elastic buckling physical performance regions of the corrugated board.

4.4 The Mathematical Models of Correlating the Strengths of Board

To provide predictive mathematical models to the corrugating industry, by assessing the physical characteristics of paper substrates and the link between the same and different conversion processes, it was also necessary to ascertain whether these models could be utilized to predict corrugated board performance under various operating and changing settings. It can use the models to choose appropriate paper substrates for making corrugated board with the required compression strength to achieve a specified mechanical performance under various conditions. The models can also be utilized for process optimization aimed at meeting targeted paper substrate, board performance at runnability condition.

4.4.1 Analysis of Variance

When there is one parametric dependent variable and one or more independent variables, analysis of regression is a statistical test for identifying variations in group means [97] . Source means "the source of the variation in the data. The possible choices for a one-factor study, such as Factor, Error (the variability within the groups), and Total (the total variation in the data from the grand mean). The factor is the characteristic that defines the populations being compared.

DF means "the degrees of freedom in the source.", SS means "the sum of squares due to the source." MS means "the mean sum of squares due to the source." F means "the variance value”, P means "the P-value calculated with a confidence interval of 95 percent is displayed as follow":

To obtain the percentage of contribution Summarizing all the sum of squares terms (SS) and then dividing each SS by the sum of SS and multiplying by 100 yields the percent contribution.

4.4.2 Analysis of Variance of PAT

Table 4.4. 1: Analysis variance of experimental data for RS165,185,205,220 at 80m/min PAT with ECT.

Source	DF	SS	Contribution %	MS	F	P-value
RS165/80	1	5643	41	5643	5.51	0.046
Error	9	8195	59	1024		
Total	10	13838	100			
RS185/80	1	11037	40.45	11037	5.4	0.048
Error	9	16247	59.55	2031		
Total	10	27284	100			
RS205/80	1	6867	43	6867	6	0.004
Error	9	9215	57	1152		
Total	10	16082	100			
RS220/80	1	5721	44	5721	6.3	0.04
Error	9	7273	56	909		
Total	10	12994	100.00			

From table 4.4.1 the experimental data analyzed the variables of pin adhesive and compression strength both unit of expression newton RS220/80 the higher contribution is 44% and RS185/80 the lower contribution of 40.45%.

Table 4.4. 2: analysis variance of experimental data for RS165,185,205,220 at 50m/min PAT with ECT.

Source	DF	SS	Contribution%	MS	F	P-value
RS165/50	1	2943	64	2943	14	0.005
Error	9	1651	36	206		
Total	10	4594	100			
RS185/50	1	8438	54	8438	13	0.015
Error	9	7190	46	899		
Total	10	15628	100			
RS205/50	1	7557	56.45	7557	10	0.012
Error	9	5829	43.55	729		
Total	10	13386	100			
RS220/50	1	6338	54	6338	9.4	0.015
Error	9	5387	46	673		
Total	10	11725	100			

From table 4.4.2 the experimental data analyzed the pin adhesive and compression strength of fabricated by 50 m/min RS165 the higher contribution is 64% and the minimum is RS185and RS220 are 54% contribution.

4.4.3 Analysis of Variance of PAT with Displacement

Table 4.4. 3: analysis variance of experimental data for PAT with displacement.

Source	DF	SS	Contribution %	MS	F	P-value
RS 165-220 /80/5 with DS (mm)	4	5492.5	59	5492.5	11.4	0.01
Error	32	3862	41	483		
Total	36	9354	100			

From table 4.4.3 the experimental data analyzed the delamination force and displacement at RS 165cm the higher contribution is 62.56 % and the minimum 54.7 % contribution for RS205.

4.4.4 Analysis of Variance of RC with Paper Substrate

Table 4.4. 4: analysis variance of experimental data for paper RC with paper substate

Source	DF	SS	Contribution %	MS	F	P-value
RC (KN/m) with paper thickness (mm)	3	0.007	3.3	0.007	0.3	7.64E-14
Error	24	0.205	96.7	0.026		
total	27	0.212	100	4.315205	255.6317	

From table 4.4.4 the experimental data analyzed RC paper substrate 1.7 and 2% insignificant impact on the paper substrate contribution at both test liners and next the fluting paper contribution is 3.3 %.

Table 4.4. 5: analysis variance of experimental data for paper RC with paper grammage.

Source	DF	SS	Contribution %	MS	F	P-value
RC at CD (KN/m) with paper (gsm)	3	98	55	98	10	0.014
Error	24	80	45	10		
Total	27	178	100			

From table 4.4.5 the experimental data analyzed the compression strength of paper substrate with paper grammage 51.57% and 60.57 % lower and higher contribution at fluting and testliner1 respectively.

4.4.5 Analysis of Variance of ECT with Board Caliper

Table 4.4. 6: analysis variance of experimental data for paper ECT with paper thickness.

Source	DF	SS	contribution%	MS	F	P-value
(ECT) with H(mm)	3	0.1161	3	0.75	7	0.018
Error	27	1.98	97	0.11		
Total	30	2.73	100			

From table 4.4.6 the experimental data analyzed variables of the compression test with caliper from 4.6% contribution is the higher and the lower contribution is 0. 36%. This thesis conducted to have added to the information available to address the linear fit between PAT and ECT at the variables of RS165, RS185, RS205, RS220 cm fabricated at 80 and 50 m/min and, paper grammage and paper thickness, RCT and paper thickness, paper grammage and RCT, ECT and board thickness.

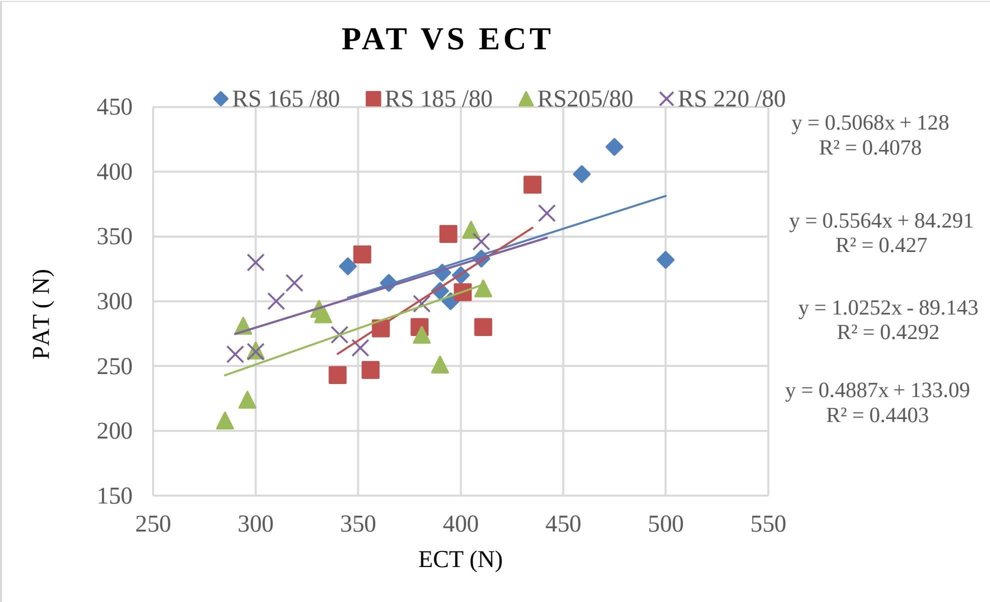


Figure 4.4. 1: linear relationship between PAT vs ECT value of RS165, 185,205 &220 cm at 80m/min.

The bonding between the fluting and test liners is assessed using the Pin adhesion Test (PAT) compression test (ECT), the amount of force needed to use an exclusive sample holder to separate the linerboard from the fluting is known as adhesion resistance and compression strength of the corrugated board at the reel size, the speed to manufacture the CFB, the flexo printer use as well as the overall dimension of the corrugated box.RS165,185,205,220 cm fabrication at 80m/min the experimental data were shown at appendix D table 1.1 and 1.2 and figure 4.4.1 to estimate the regression analysis comparing the measured ECT with PAT. The coefficient of determination (R^2) is 0.41,0.43,0.43 and 0.44 based on the finding result from 41-44% of contribution, when their relationship is linear the impact of intermittent glue application and glue line skipping on ECT, by pin adhesion loss and the glue skip can result loss of ECT.

Figure 4.4.2 shows that the correlation between PAT and ECT at the fabrication of 50 m/min the coefficient of determination is R^2=0.64, R^2=0.54, R^2=0.56, R^2=0.54 this means as compare to the two variables of the PAT vs ECT value of RS165, 185, 205 & 220 cm at 80 and 50 m/min shows the statistical correlation of the fabricated samples by taking into account the sign of the coefficients R^2, the equation in table 4.4.8, The variables of both summarized equations were statistically significant and accounted for 42.6 and 59% of the pin adhesion and compression strength. The measurements are displayed in Figure 4.4.1 and 4.4.2 the later demonstrates that the compression strength rose, stronger pin adhesion strengths were attained. It looks likely that better glue penetration at the fabrication of 50m/min and the strength contents is what has caused the improvement in adhesion strength.

It takes more effort to sponge than a damp one, according to this investigation, the advantages of increased the strength at reach a maximum of 27.8% that of fabricated by 80m/min the starch may penetrate too quickly, starving the starch for water and reducing adhesion strength. Because of glue skips or because some of the weaker bonds cannot withstand the forces brought on by ECT testing, low pin adhesion strength is known to diminish ECT.

ECT and PAT spanning the speed range of 50 and 80 m/min at a constant and the same types of adhesion was marginally lowered as corrugating speed was increased. Losses in ECT would be anticipated if this happens, as pin adhesion frequently declines at greater speeds. For the paper substrate at the set of liners and fluting, the compressive strength of the medium plays a significant role in ECT. Reduced pin adhesion strength and higher high-lows caused by corrugating will lower ECT and prevent the liners and medium from reaching their full compression capability at the speed from 80-95m/min.

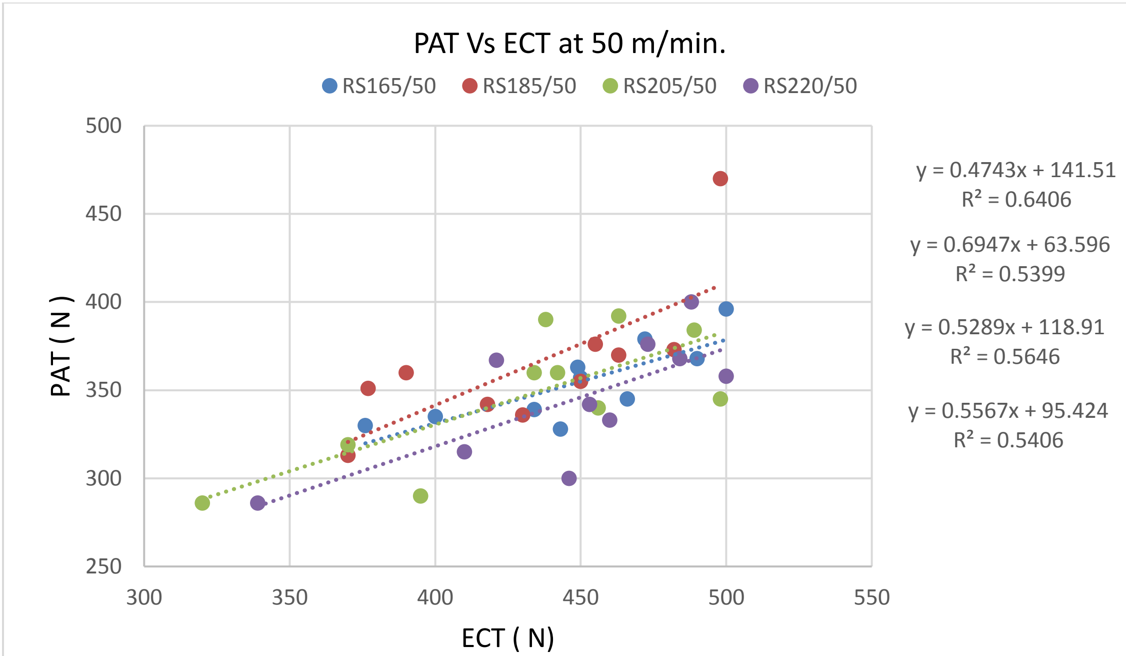


Figure 4.4. 2: linear dependence between PAT vs ECT at RS165, 185,205 &220 cm at S 50m/min.

PAT at 80m/min (N)=0.644*ECT(N)+64……………4.1

PAT at 50m/min=0.6136ECT(N)+82.2………………4.2

10N change in ECT would be anticipated for a change of 70.44 and 88.33 Newton in pin adhesion strength at equation 4.1 & 4.4 respectively. Reel size fabricating speed and material property influence the relationship between pin adhesion and box performance. Fabricating speed and reel size of the paper impair box strength an average of 40,65 % at 80,50 m/min. The impact of intermittent glue application and glue line skipping on ECT and BCT may be exacerbated by pin adhesion loss. The glue skip can result loss of ECT, Furthermore, the effects of glue line skip combined with a hefty board would have a greater impact on compression performance.

Figure 4.4.3 shows that the correlation between Delamination and displacement is R^2=0.5786, R^2=0.6256 R^2=0.547, R^2=0.5946 the two tests has shown the strength as the function of the displacement value. The experimental data were shown at appendix D table 1.3, After printing the coefficient of determination between the variable's linear relationship after printing the strength of the corrugated board of the delamination rescued at the variable of fabricated board at 80 m/min and printing machine the higher the pin adhesive strength take the maximum deflection to separate the liners from fluting at the same time the less force need to separate the paper at less displacement, printing roller size, slotting ,folding ,board dimension, has the impact for reducing at the lower deflection and less retention fluting on the board.

PAT = 27*(Displacement)+159.44……….4.3

At the change of the deflection of the strength of the board, the delamination strength of the pin value increasing at the confident of 59%.

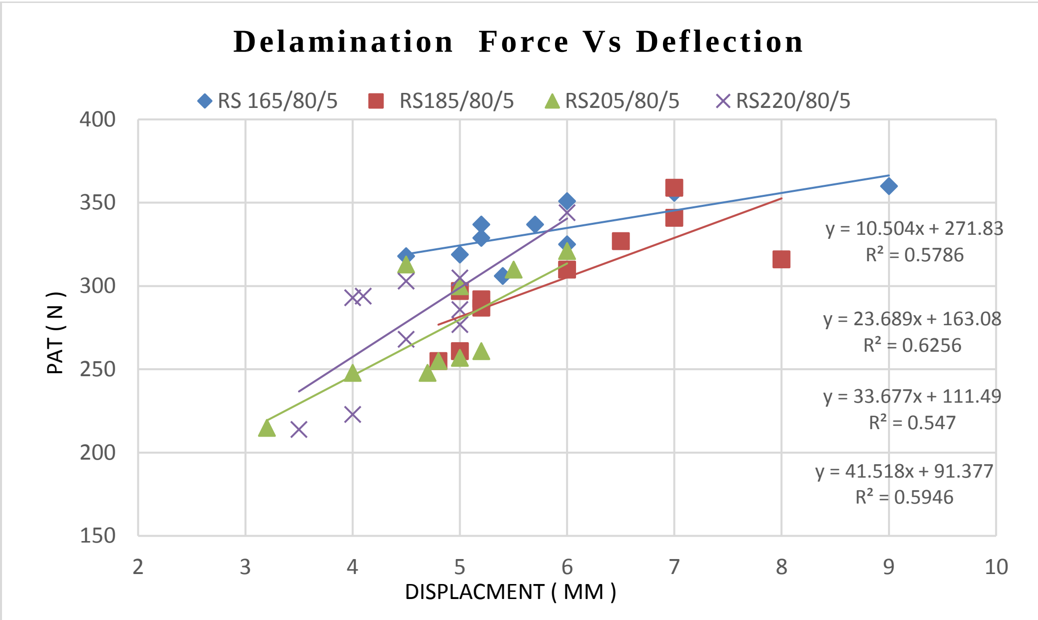


Figure 4.4. 3: correlation of linear fit obtained Experimental result of delamination and displacement.

Fig 4.4.4 It is possible to accurately anticipate the compression strength of corrugated board using the resulting value by displaying the measured paper compression strength (RCT) prior to exposure under conversion conditions.

This implies that a drop in the measured fluting paper compression strength using either of the employed variables could be caused by a decrease in the edgewise crush strength of the corrugated board. The correlations between the test findings of the reel size at operating speed varies, different strength reduction outcomes are anticipated. Despite the fact that the strength reduction achieved using the findings of the variables is not the same in amount, the loss in the board's compression strength is comparable with the loss in strength of its materials during processing.

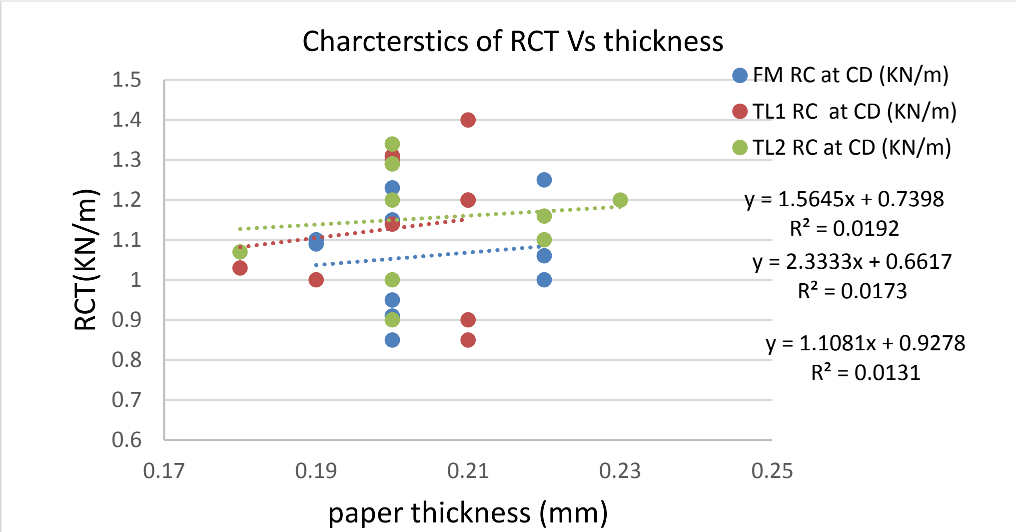


Figure 4.4. 4: Relationship of RCT and paper thickness.

The correlation between the paper thickness and the RCT result obtained as Fm, TL_1,TL_2 R^2=0.0192, 0.0173, 0.0131 respectively the coefficient of determination is 1.92, 1.73 and 1.31%.

RCT (KN/m) =5*(Paper thickness) + 2.33…………...4.4

To summarize the above equation 4.4, the impact of the paper thickness is insensitive and the linear relationships of the compression strength to paper thickness is 1.67% of determination.

Figure 4.4.5 To assess and compare the RCT and the physical properties of paper approaches are important for the developments and management of paper quality for the sake of converting process to identify the compression strength of the combined board.

The comparative results in this test could confirm that good correlations with the boards' ECT results exist, regardless of the paper test variables used during fabrication condition. The comparison of the model's relationship between grammage and RCT for the paper using for fabricated the board property fitting to experimental data demonstrates good agreement and offers linear, affordable method to estimate the contributions of grammage. The measurement has also been utilized to provide on how the fiber distribution has changed with grammage the RC of the R^2 of fluting medium, testline1 and testline2 are 0.5157,0.6057 and 0.5408 respectively. The RCT values for linerboard samples produced at the case company as the data see that over the full range of basis weight, from 129-145 g/m^2 and RCT are linearly related with an R^2 value of 0.55, implying that 55% of the RCT value can be accounted for by a linear fit with paper grammage. The approaches do, that it could use the equation presented to convert from one property to the other for any given grade of paper

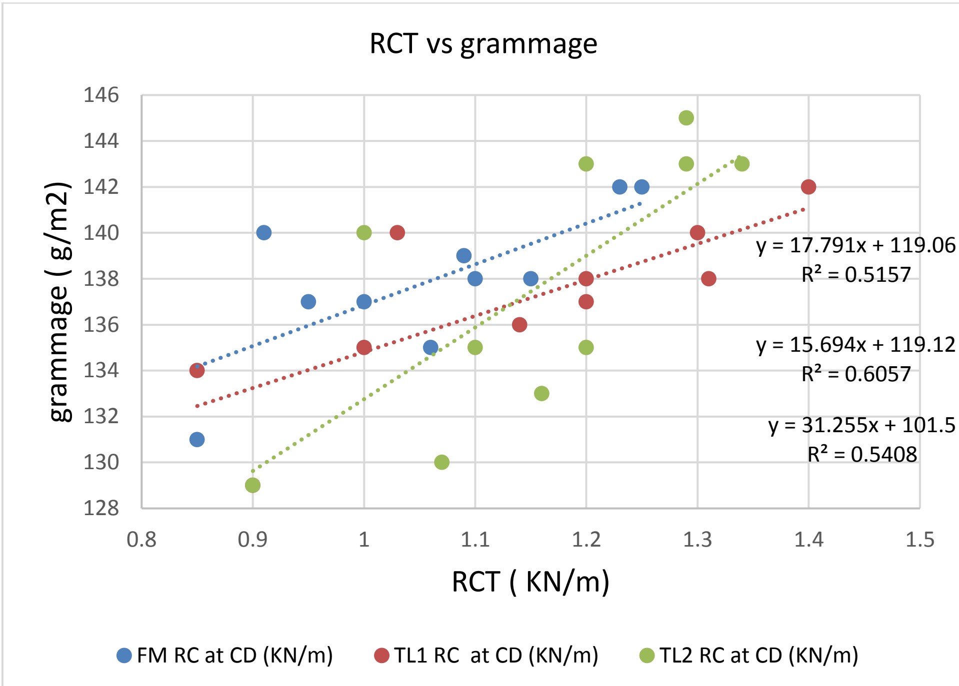


Figure 4.4. 5:linear relationship between measured RCT and grammage of corrugated papers.

, Further, this data includes papers made with recycled content, refined at different levels, and subject to variation in strength of the paper making process, telling the quality of the fabricated board and to identify the source of effects to weakened the board through process either the material itself as long as the manufacturing variables helped to make the board stronger. There are relatively more and fewer things when the board is processed with different variables, a critical input to the fabricating process and directly related the strength of ring crush results in an increasing the mechanical strength of the combined board. When creating a mechanistic model of box performance, understanding basic material qualities and how they interact might be crucial.

RCT (KN/m) =21.58(g/m^2) +113.22 ……….4.5

Uneven paper thickness as well as inconsistent paper weight can play a major role in the results obtained. the failure mode is mainly bending or buckling of the paper sheet structure, fiber to fiber impregnation lack of compactness and the intensity of compression strength of the paper band to grammage. The linear fit obtained are referred to 55% of the variability observed at the regression model.

At appendix D table 1.5 illustrates how the outcomes of this extremely robust board impose less linearity in the data fit. a regression equation relating corrugating process variables and corrugating board thickness to ECT is presented in Figure 4.4.6 The data were generated using RS220/50, RS220/50/5, RS165/80, RS165/80/5 corrugator board fabricated at corrugating mediums fluting, testliner1 and testline2 thickness. the relationship between board thickness and the edge compression strength board. The coefficient of determination R^2=0.0361,0.0299,0.0036,0.0465 and it is insensitive at the two variables of their linear correlation.

ECT(KN/m) =3.74*(caliper) + 0.77…….4.6

The fact that the statistical relationship between the thickness of the board and the compression strength is small shows that the main thing that affects the strength of the board is the type of raw material and the processing condition that use, but the thickness of the board has 0.3-5 % determination.

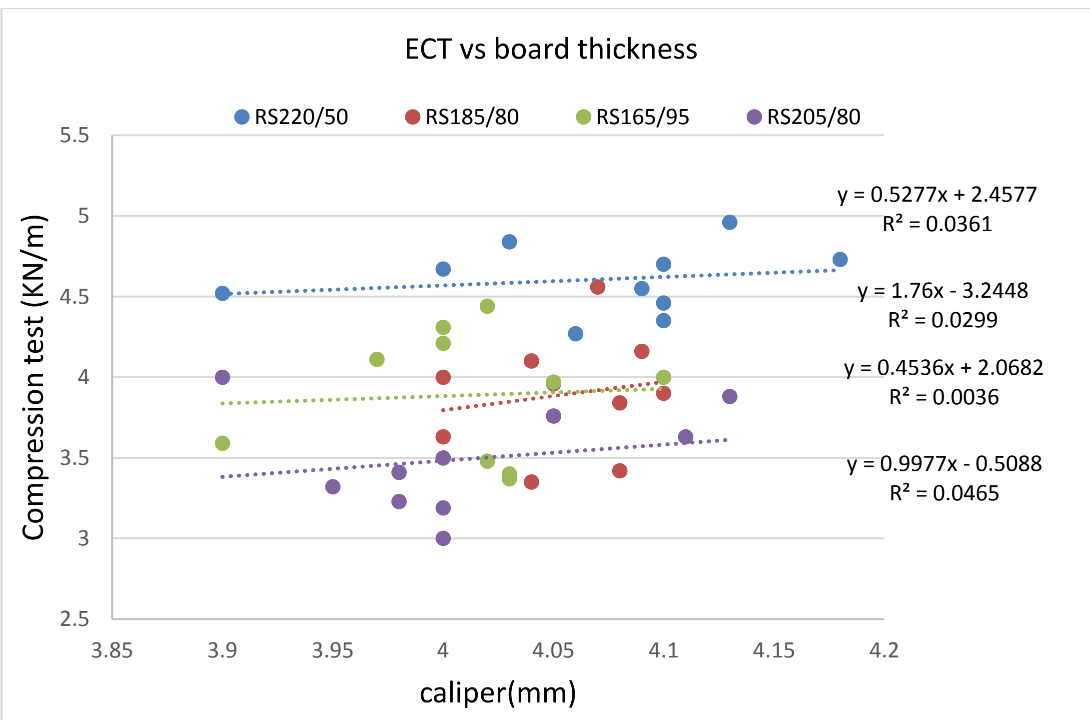


Figure 4.4. 6: The linear relation between the compression resistance (ECT-value) and the corrugated board's caliper (thickness-value).

The recorded PAT, ECT, RC, and physical characteristics of paper with variables that used compression strengths revealed that the coefficients of determination are positive such as paper thickness with RCT, ECT with board caliper. This shows that these relationships can be quite useful in understanding the variables in depth when predicting the box compression strength of corrugated board while taking the model and the manufacturing process into account. The link between the variables PAT and ECT, PAT and deflection, RCT with paper grammage, board thickness and compression strength were then predicted using the linear regression equations at table 4.4.7.

Table 4.4. 7:linear mathematical models for corrugated board, and paper at different variables.

Group types	Types of variables	Equation	Types of relation and units of Expression	R^2
Figure 4.4.1	RS165/80	Y=0.5068x+128	PAT (Newton) and ECT (Newton)	0.4078
	RS185/80	Y= 0.5564x+84.291		0. 427
	RS205/80	Y= 1.0252x-89.143		0.4292
	RS220/80	Y=0.4887x+133.09		0.4403
Figure 4.4.2	RS165/50	Y=0.6396x+66.3	PAT (Newton) and ECT (Newton)	0.6467
	RS185/50	Y= 0.6947x+63.596		0.5399
	RS205/50	Y=0.5289x+118.91		0.5646
	RS220/50	Y=0.5567x+95.424		0.5406
Figure 4.4.3	RS165/80	Y=10.504x+271.83	Force (N) and Displacement (mm)	0.5786
	RS185/80	Y=23.689+163.08		0.6256
	RS205 /80	Y=33.677x +111.49		0.547
	RS220/80	Y=41.518x +91.377		0.5946
Figure 4.4.4	F_M	Y=1.5645x+0.7398	Paper substrate RCT (KN/m) and paper thickness (mm)	0.0192
	TL_1	Y=2.333x+0.6617		0.0173
	TL_2	Y= 1.1081x+0.9278		0.0131
Figure 4.4.5	F_M	Y=17.79x+119.06	Paper substrate RCT (KN/m) and paper grammage (g/m^2)	0.5137
	TL_1	Y=15.69x+119.12		0.6057
	TL_2	Y=31.25x+101.5		0.5408

Figure 4.4.6	RS220/50	Y=0.5277x+2.4577	ECT (KN/m) and board thickness (mm)	0.0361
	RS185/80	Y=1.76x-3.2448		0.0299
	RS165/95	Y=0.4536x+2.0682		0.0036
	RS205/80	Y=0. 9977x+0.5088		0.0465

By using the equations in this way, it is possible to assess the potential effects of process optimization on corrugator operating methods. Since glue skips are present or some of the weaker bonds are unable to withstand the forces brought on by ECT testing, low pin adhesion strength is known to diminish ECT. At the correlation between box strength and deflection that may be used to forecast the compressive strength of boxes end to end as well as take into account different box sizes, and pure compressive strength. The mathematical model for predicting the top-to-bottom compressive strength and their interlinking during the fabrication process shows that the box mechanical performance is determined by the size of the box (as indicated by the box perimeter), by the pure compressive strength of the combined board (as indicated by the CD Edge Crush Test). As stated in chapter two paragraph 2.10. a 10% reduction in pin adhesion strength results in a 3.3% loss in the combined board's Edge Crush Test and a 2.5% loss in top-to-bottom box compression.

4.5 Quality Chartcerstics on Adhesive Strength of The Fabricated Board

The reel size 220 cm fabricated at 95m/min has higher susceptibility to failure than the others reel size such as 165,185 and 205 cm, according the laboratory tests. The results indicate that if 205 is also produced in 95m/min, it would be less adhesive strength boards exhibited. The raw material is important for fabricated, and this material property test has its own role in the obtained results. Similarly, the strength and failure of selected boards were observed in relation to the reel size of the fabricated corrugated fiber board, increasing speed in all reel sizes the compression, the pin adhesive as long as the board strength decreased and defect will lead to the box failure will be occurred at unexpecting time.

RS205 and 220 cm, at the speed of 95m/min is mostly exposed to waste when it is fabricated. the pin adhesive and compression results are between 50-80 m/min is more than what was produced at their strength. This is because it is a defective sample and it is not strong enough to resist the applied load and careful about the results, it may seem strong. therefore, if up to 85m/min the reel size is fabricated, it is possible to obtain corrugated boards of different strength, but more than the ones can manufacture waste and very weak boards can be obtained. In addition, if reel size 165 and 185cm at 95m/min are produced, the result shows that they have different board strength, and if produced more than that, the board strength may be weak and defect may be high as mentioned as RS205-220. Two things can cause this defect at the ends or all down the length. The corrugator faces are the breaking of flutes, which causes the flutes to lose their strength and adhesive effect on the corrugated box's performance, lowering the finished box's compression strength and the mechanical qualities should be fully occupied by each layer.

4.6 Process Evaluation the Fabricated Corrugated Fiber Board

The board quality and subsequent box performance can be improved based on the results finding, such as fabricating speed, types of paper, reel size and for the purpose of penetrating glue inside, viscosity. Since adhesive formulation, component porosity or hydrophobicity as well as corrugation conditions can affect this value, if a specific medium is said to have good runnability, from RS165-185 cm fabricated at 50-95m/min and 205-220 cm reel size fabricated at 50-80 m/min according to the experimental finding of the result has good runnabilty. PAT, ECT and BCT strong at RS165-185 cm fabricated from 50-95m/min with different results of compression strength, but fabricated by 50 m/min higher.

Quantification helps to identify differences in the strength of the manufacturing process when summarizing the regression analysis in the table 4.4.7, the PAT and ECT at 50 and 80 m/min, the confidence of determination is 59% and 43% respectively. The linear fit between PIN and ECT when fabricated at 50 m/min higher and less at 80m/minute, the ECT is strong and the result of PIN is the same at first case. The direct correlation of force with deflection is R^2 value 0.5865, which means 58.65% of the force value can be explained by a linear fit using delamination with displacement. The linear correlation between the paper compression strength and the paper grammage are linearly related with average R^2 result of 0.55. Board caliper, paper thickness is less coefficient of determination with the compression strength of the r^2 value 0.03 and 0.02. By using the edge crush test result at table 4.4.2 can obtain the McKee box prediction on table 4.4.8 only be used with RSC boxes that have a perimeter to width ratio more than 1/7 the board thickness 4mm and when it is made in a board box geometry 300*300*280. This equation is nevertheless valid for a statistically guaranteed number of boxes of various sizes and made of various corrugated boards despite the item it contains. some of these elements have to do with box design, manufacturing procedures, and structural characteristics at the fabrication of 50 ,65,80,95 m/min, multiplied the theoretical value as per the condition of it contain inside the box from 0.625-0.4824 to predict the box strength or take the maximum and the minimum, to calculate the theoretical value by 0.55 and taking the average of 0.6 (114/184) and 0.5(61/125) by consider is the ECT the board caliper and the box geometry.

According to this whose value of the ECT more than 4 KN/m of box size 300*300*280 mm can with stand 112-114 kg at the top of compression.to optimize the BCT property by using McKee equation to convince the corrugated manufacturers to know in detail to the excellence of the products.

Table 4.4. 8: actual and McKee box prediction.

CBFS(m/min)	MBP (kg)	Actual (kg)	Expected BC(Kg)
RS165/50	184	114	115
RS185/50	176		115
RS205/50	175		115
RS220/50	184	112	112
RS165/65	176		115
RS185/65	161		89
RS205/65	157		87
RS220/65	151		84
RS165/80	166		92
RS185/80	146		81
RS205/80	136		75
RS220/80	125	85	85
RS165/95	154	81	85
RS185/95	130		72
RS205/95	123	Delamination high at the corrugated fiber board.	
RS220/95	119		

The suitable fabrication speed is from 150-185 cm reel size up to 95 m/min RS190-205 up to 85m/min and above RS205 up to 80 min the fabricating process to be optimum and can be obtained different compression strength according to the fabricating condition of the variables. The corrugated board must run well on the corrugator at optimum speeds and they must have good runnability and strength characteristics. It is estimated that the raw material or input that use will be good for the quality of the corrugated box strength, but using the variables at optimum production conditions, and the strength of the board can be determined by the experiment thorough the reel size. Based on this whose value of edge crush test from 4-4.75 KN/m fabricated by 50m/min and RS165/65m/min at RS165-220 for the box made, the result can be higher or lower, depending on the quality of the raw material used and the converting process, has the pure compression strength is 112-114kg, the nature of the fibers in the corrugated board and the geometry of the box utilized for the box construction, the BCT test is just an estimate of the box's weight carrying capacity. It is carried out in a box crush tester in a relatively short amount of time.

To determine the box's real stacking performance, the BCT result must be divided by a stacking (or safety) factor (SF). The common denominator SF for general packaging is 3-5, therefore if the BCT test fails with a weight of 114 kg, the box can only be utilized if the load it must support is less than 33 kg. Compression creep occurs during the course of the time the box is under load, which accounts for the significant discrepancy between what the BCT measures and what is realistic to use. Changes in the moisture content of the box panels under cyclic humidity environmental circumstances speed up this compression creep in many common instances.

Corrugated boxes always face the risk of compression, particularly if heavy loading takes place, harming the goods inside. Corrugated box testing methods provide key information for companies to design or rethink their packaging, as they determine maximum compression forces that the company's boxes can endure.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Factor in determining box compressive strength performance is the variable of strength (ECT, PAT, Box geometry). In particular investigating samples into which can incorporate the reel size, corrugating speed, box geometry and mathematical relationship between these parameters. This would allow to apply and growing the understanding of how variables are impacted by factors related to corrugated board. Based on knowledge of the board geometry and compression strength variables, evaluate the fabrication process regarding the compressive strength values for combination corrugated fiber boards.

To improve the strength of the corrugated board by relating it to the reel size during processing variables. It creates an optimum fabricating process at which the board strength is runnabilty for the different variables such as reel size and speed. They evaluated the optimum process to get the strength of the board regardless of which speed, reel size it works, and observed the effects of process or quality problems on the corrugated board in practice.

- As fabrication speed and reel size increase, the pin adhesive strength decreases. The RS165 was fabricated in 50/65 m/min at the similar result 354.7 and 356 N. While the 80/95m/min the resistance to separate the liners from the fluting reduced by 5.75,14.5,12.94%. The other RS185,205,220 the speed increases their force of delamination strength decreased from 1.4-27 % at the fabricated speed of from 65-95m/min for RS205 from 2.4-26.9% and for RS220 from 5-30.2% the pin adhesive strength reduced and delamination likely at increasing the fabricated speed.
- The characteristics of the material, the corrugated fiber board fabricating speed, reel size, and this will contribute to the strength of the board, and the quality of the glue will have its own contribution. PAT is used for this purpose to identify glue strength and defect of the board to identify individual as well as related conditions.

In order to determine the strengths of the board and its components, the compression strength test techniques should be used in accordance with the maltfort equation $ECT = k (\sigma c,L_1 + \sigma c,L_2 + \alpha\sigma c,F)$ during converting process. The theoretical ECT Compression Test and actual Ring Crush

Test (RCT) are the two methods in the fabrication process for testing paper compression strength is vital. The combined effect of the different reduction in strength of the components was reflected in the ECT increasing and reduction strength after exposure to 50-95m/min at reel size of 165-220cm conditions for the same paper substrate. the lower reduction in ECT after exposure conditions above at running speed of RS185, RS205, RS220 at 80and 95m/min.

- The ECT strength varying effect is directly proportional to the final box strength. Stronger load bearing capacity of the box RS165,185,205,220 fabricated by 50 m/min and the strength of the manufactured corrugated board stronger than other from 5-33% variation has been occurred.
- RS 165 and 220 cm have pure compressive strength of 114-112 kilograms of board fabricated at 50 m/min, while RS 165cm at 95m/ and RS 220 at 80 min has a strength of 81and 85 kilograms, which means that the corrugated board produced at a fabrication speed of 50-95m/min can bear from114-81 kilograms. This enables allows the variables can use to determine the packaging strength depending on the function of the contains item inside the box.
- The same box length 300mm and width 300mm but at different height of 150,200,250,300,350 mm at RS205 at the fabricated speed of 50m/min the compression strength reduced by 8-24.7% consecutively. The shorter the height the compression strength is greater, the higher the height the box can be buckling locally and globally then easier to fail.

The linear fit ECT, PAT, RCT, deflection, paper and board properties have been clearly taking significant structural and component properties into consideration during fabrication process. These models may be utilized for thorough to know the strength and its effects for practical use and runnabilty condition.

- The result indicated that the coefficient of determination between ECT and PAT the R^2 0.4267,0.59. This imply that at 50m/min is 59% an increase the ECT value the same to PAT but at the fabricating variables on 80m/min 42.6% and less than 16.4% of the PAT and ECT at 50m/min which means 43% and 59% of the force value can be explained by a linear fit using delamination with compression strength.

- The relevance of RC compression strength to paper corrugating components is needed which have the best properties for fabrication, conversion and end-use performance. The RCT values for linerboard samples produced at the case company as the data see that over the full range of basis weight, from 129-145 g/m^2 and RCT are linearly related with an R^2 value of 0.55, implying that 55% of the RCT value can be accounted that the analysis of variance was carried out using the known linear equation by a linear fit with paper grammage.

The above variables are applied during the fabrication of the board, the bearing capacity of the corrugated box, experimentally functional and the results will be helping to evaluate the process and providing the effects of variables on the mechanical performance of the corrugated fiber board. However, this situation can be undermined by factors such as moisture, cyclical condition and the material packed inside the box in it, which reduces the mechanical performance of the corrugated box.

5.2 Recommendation

So as to reduce the high/low corrugator profile it is better to shift right and left to fabricate the corrugated board, this will minimize the high low fluting medium. This means that if a size corrugating machine of 220 cm is repeatedly fabricated reel size at 150cm, the corrugator's teeth will not be uniform, resulting in fractures in the corrugated paper and associated variables. Moisture can reduce the strength of the box, so risk can be minimized by increasing the factor of safety at the same time considering the box item and contained at the container inside it. Adding a piece of board strip in every corner and in the middle to withstand the various impact pressures that the board will face after it is manufactured and to provide strength. the stiffness to be strong to add additional strength, to shock absorber occasionally using air-filled rubber and shock absorber (cushioning) material will increase additional mechanical strength performance used for its intended purpose.

5.3 Future Work

collecting different corrugated products and samples, measuring their strength and exploring variables, if it is focused on future in which address the following study: -

- Analyzing the compression strength of board and ring crush test of by the paper substrate using Finite Modeling and simulation.
- Based on the process variables, by collecting different corrugated fiber boards and measuring the RCT of the raw materials used, the improvement in strength is explored.
- Effects of Recycled paper on the strength of corrugated board during fabrication process and number of recycled on strength loss of fiber.
- There is a study and research on chemical impregnation that improves the strength of paper at paper mill.

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Appendix A: Test Result of Pin adhesive (Delamination)

	RS165				RS185				RS205				RS220			
	50	65	80	95	50	65	80	95	50	65	80	95	50	65	80	95
	325	346	333	331	400	293	300	302	413	342	208	256	331	357	395	275
	405	365	368	243	333	310	343	275	344	354	281	294	293	406	246	296
	338	314	400	316	354	352	280	333	352	269	315	275	359	340	360	255
	367	370	327	355	363	348	236	292	295	408	251	201	378	333	261	181
	325	354	314	319	303	282	319	253	365	376	393	259	382	355	274	263
	342	417	319	291	347	387	347	331	392	316	262	307	321	268	217	364
	353	347	320	306	349	366	269	309	289	380	395	169	416	379	319	190
	359	352	322	249	352	398	370	268	310	348	294	247	318	311	264	271
	365	339	332	341	356	359	390	219	363	301	370	350	339	306	253	166
	368	362	308	281	362	372	350	289	385	327	230	205	352	259	311	174
Sum	3547	3566	3343	3032	3519	3467	3204	2871	3508	3421	2999	2563	3489	3314	2900	2435
avg	354.7	356.6	334.3	303.2	351.9	346.7	320.4	287.1	351	342.1	299.9	256	349	331	290	244
stedv	24.01	26.42	28.3	37.282	24.36	39.2515	48.5505	35.08	41.8	40.889	67	54.3	36.3	46.5	55.4	64.2
var	576.7	698.3	800.7	1390	593.4	1540.68	2357.16	1231	1748	1671.9	4489	2947	1315	2160	3068	4127

Table 1. 1 data for PAT, at RS 165, 185,205,220 cm at fabricated speed of 50/ 65/80/95m/min

	RS165/80	RS165/80/5	RS185/80	RS185/80/5	RS205/80	205/80/5	RS 220/80	220/80/5
	333	314	357	262	287	218	295	259
	378	305	243	349	295	291	246	239
	300	307	370	242	330	315	360	255
	327	280	236	366	251	227	261	234
	402	311	395	261	315	301	274	227
	359	308	347	294	362	228	317	210
	320	314	329	218	340	281	279	305
	352	349	279	350	294	265	294	205
	332	328	388	303	330	285	353	311
	308	329	290	244	230	218	300	215
avg	341.1	314.5	323.4	288.9	303.4	262.9	297.9	246
sum	3411	3145	3234	2889	3034	2629	2979	2460
std	31.77	18.179	58.098	52	41	37	37	37
var	1009.6	330.5	3375.377	2695.43	1653.82	1368	1363	1383

Table 1. 2 Experimental data for PAT at 5 units printing at 80m/min.

	RS 165/65	RS 165/65/5	RS185/65	RS185/65/5	RS205/ 65	RS205/ 65/5	RS220/65	RS220/65/5	RS220/50	RS220/50/5
	346	319	293	255	342	315	357	214	331	325
	365	337	410	292	354	248	306	286	406	303
	414	356	352	359	369	348	340	223	359	260
	370	351	378	261	290	257	333	277	334	330
	354	337	282	387	376	355	355	344	382	385
	317	306	387	341	356	300	268	268	321	310
	347	325	366	297	280	261	290	294	316	309
	372	318	331	310	348	321	321	305	318	301
	339	329	359	316	355	313	346	353	339	343
	362	360	372	327	337	310	359	293	352	320
sum	3586	3338	3530	3145	3407	3028	3275	2857	3458	3186
Avg	358.6	333.8	353	314.5	340.7	302.8	327.5	285.7	345.8	318.6
Sum	3586	3338	3530	3145	3407	3028	3275	2857	3458	3186
Stedv	25.51	18	40.5	41	32	37	31	45	29.5	32

Table 1. 3 Experimental data for PAT at 5 units printing at 65 m/min.

	RS165/95(N)	Displacement(mm)	RS185/95(N)	Displacement(mm)	RS205/95(N)	Displacement(mm)	RS220/95(N)	Displacement(mm)
	356	7	273	5.4	263	3.2	258	4.5
	303	5.2	280	5.2	283	4.7	270	4.5
	315	6	300	4.5	252	4	254	4
	296	4.7	289	5	278	5	289	5
	301	5.7	290	5.2	282	4.8	264	4.3
	298	5.4	295	4	231	3.8	240	3.5
	310	4.6	298	6	306	5.2	275	4.1
	305	4.5	287	4.5	277	4.6	255	4.7
	309	5.2	290	4.8	250	4	265	4.5
	294	5	286	6.5	312	5.5	238	3.5
avg	308.7	5.144	288.8	4.857	273.4	4.48	260.8	4.233
sum	3087	53.3	2888	51.1	2734	44.8	2608	42.6
sted	17.87	0.755	8.093	0.738	25.087	0.71149	15.454	0.49
var	320	0.5712	65.51	0.545	629.377	0.5062	238.84	0.24

Table 1. 4 Experimental data for PAT VS deflection at 95 m/min.

Appendix B: Tested Result of Edge crush and Material property test

	ECT of RS165cm (KN/m)				ECT of RS185cm(KN/m)				ECT of RS205(KN/m)				ECT of RS220(KN/m)			
	50	65	80	95	50	65	80	95	50	65	80	95	50	65	80	95
	4.22	4.69	4	3.87	3.87	4	3.44	3.25	4.18	3.98	2.9	2.89	4.6	4.1	2.78	3.9
	4.93	4	3.6	4	3.89	4.71	4.35	3.88	3.89	3.3	3.9	2.91	3.2	4.33	2.85	3.22
	4.33	4.12	4.2	3.61	4.55	3.96	3.62	3.55	4.21	4.14	4	2.99	4.3	3.37	2.89	3
	4.87	4.82	4.4	4.18	4.73	4.16	4	3.17	3.23	3.18	3	3.61	4.4	4.31	3.91	3.25
	4.46	3.93	4.1	3.46	4.33	3.28	3.7	3.6	4.34	3.93	4	3	4.5	4.45	2.99	3.39
	4.31	4.32	3.5	4.53	4.35	4.81	3.87	4.61	3.67	3.26	4.1	3.51	4.5	3.49	3	2.43
	4.82	3.89	4.2	3.27	4.34	4.39	3.61	3.65	4.67	4.35	3.9	3.83	4.7	2.53	4.01	3.38
	4.34	3.91	4.3	3.91	3.75	4.14	4.29	3	4.71	3.95	3.2	3.15	4.7	3.58	3.55	2.58
	3.66	4.52	3.8	4.4	4.45	3.86	3.48	3.72	4.85	3.41	2.7	3.19	4.7	3.63	3.1	2.33
	4.51	4.19	4	3.43	4.21	4	3.92	2.89	4.41	4.48	3.3	2.26	4.8	2.74	3.12	2.24
sum	44.45	42.4	40	38.7	42.5	41.31	38.3	35.3	42.2	38	35	31.3	44	36.5	32.2	29.7
avg	4.445	4.24	4	3.87	4.25	4.131	3.83	3.53	4.22	3.8	3.5	3.13	4.4	3.65	3.22	2.97
sted	0.376	0.34	0.3	0.42	0.32	0.438	0.32	0.5	0.5	0.47	0.5	0.44	0.5	0.66	0.44	0.55
var	0.141	0.11	0.1	0.18	0.1	0.192	0.1	0.25	0.25	0.23	0.3	0.2	0.2	0.44	0.2	0.3

Table 1.1 Experimental data for ECT

	RCT at CD (KN/m)			Theoretical ECT
	TL1	Fm	TL2	
	1.31	0.95	1.2	3.6975
	1.2	1.09	1	3.5625
	1	0.85	0.9	2.9625
	1.3	1.15	1.29	4.0275
	0.9	1	1.34	3.49
	1.4	1.06	1.2	3.925
	0.85	1.1	1.16	3.385
	1.03	1.23	1.07	3.6375
	1.14	0.91	1.1	3.3775
	1.2	1.25	1.29	4.0525
sum	11.33	10.59	11.55	36.1175
avg	1.133	1.059	1.155	3.61175
sted	0.183	0.1324	0.139	0.336
var	0.033	0.0175	0.019	0.113

Table 1.2 Experimental data for RCT and predicated value of ECT

	RS220/50	RS220/50/5	165/80	165/80/5	RS185/95	RS185/95/5	RS205/95	RS205/95/5
	4.55	3.96	3.98	2.94	2.82	2.88	2.77	2.8
	3.2	3.35	3.59	3	3.83	3.4	2.9	2.94
	4.27	4.16	4.21	4.12	2.69	3.09	2.83	3
	4.35	3.42	4.37	3.19	4	3.92	2.85	3.48
	4.46	3.81	4.11	3.23	3.55	2.65	4.12	3.19
	4.52	3.63	3.48	4.09	4.19	3.27	3.32	2.55
	4.7	4.1	4.24	3.32	3.33	3	3.56	3.29
	4.67	4.56	4.31	3.36	4.1	3.87	3.41	3.11
	4.73	3.84	3.77	3.41	3.95	2.91	3.59	2.69
	4.84	4	3.97	3.5	4.34	4.13	3.45	3.72
sum	44.29	38.83	40.03	34.16	36.8	33.12	32.8	30.77
avg	4.429	3.883	4.003	3.416	3.68	3.312	3.28	3.077
sted	0.466	0.360	0.30	0.40	0.57	0.50	0.437	0.3596
var	0.217	0.13	0.09	0.16	0.32	0.25	0.191	0.129

Table 1.3 Experimental data ECT at printing variables

	h=25mm	h=30mm	h=40mm	h=50mm	h=60mm
	4	4.01	2.97	3	2.87
	4.15	4.25	2.93	2.81	2.61
	3.33	3.11	3.18	2.52	2.56
	4.24	4.31	3.58	2.77	2.72
	4.2	4.25	3.62	2.87	2.26
	3.24	3.18	2.85	2.98	2.8
	2.33	2.19	2.9	2.75	2.55
	3.03	2.86	3.15	2.48	2.6
	3.16	3.46	3.67	2.7	2.65
	2.51	2.18	3.6	2.8	2.25
sum	34.19	33.8	32.45	27.68	25.87
avg	3.42	3.38	3.245	2.768	2.587
stedv	0.70	0.82	0.34	0.2	0.2
var	0.5	0.7	0.11	0.03	0.04

Table 1.4 data ECT at height of 25/30/40/50/60/mm at 5-unit printingRS205/65m/min

	ECT at h=25mm	ECT at h=30mm	ECT at h=40mm	ECT at h=50mm	ECT at h=60mm
	4.62	4.54	4.58	4.1	3.9
	4.91	5.17	4.19	4.33	3.82
	3.77	4.72	3.25	4	3.23
	5.11	3.4	5.14	4.01	4.25
	4.52	5.32	4.34	4.45	3.39
	5.16	4.66	3.43	4.89	2.93
	5.08	4.85	4	3.96	4.16
	3.6	5	4.76	3.58	4.88
	4.92	4	4.96	3.63	4.63
	5	3.53	4.02	3	3.68
sum	46.69	45.19	42.67	39.95	38.87
avg	4.669	4.519	4.267	3.995	3.887
sted	0.56	0.66	0.62	0.52	0.61
var	0.31	0.44	0.38	0.27	0.38

Table 1.5 data ECT at height of 25/30/40/50/60/mm RS205/50m/min

	RS220/50		RS165/65		RS185/80		RS185/95		RS205/95		RS220/95	
	ECT (KN/m)	deflection at crush force (mm)	ECT (KN/m)	deflection at crush force (mm)	ECT (KN/m)	deflection at crush force (mm)	ECT (KN/m)	deflection at crush force (mm)	ECT (KN/m)	deflection at crush force (mm)	ECT (KN/m)	deflection at crush force (mm)
	3.507	1.577	3.923	0.213	4.373	0.274	4.603	0.155	3.286	0.581	3.319	2.368
	3.309	0.107	3.769	1.7	3.155	3.289	3.149	2.159	2.761	2.041	2.528	2.055
	6.17	0.408	3.679	0.173	5.077	0.94	3.305	1.44	3.211	2.528	2.623	2.072
	5.474	0.384	6.721	0.462	5.708	0.357	3.045	2.172	3.015	2.583	2.826	1.325
	6.191	0.945	5.582	0.402	3.335	1.973	3.211	2.528	2.939	1.478	3.601	0.489
	6.001	0.381	4.174	0.453	3.315	1.6	3.144	2.494	2.973	1.23	2.976	2.09
	3.53	2.043	3.859	0.201	3.139	2.368	3.88	0.625	2.998	2.608	2.975	3.228
	3.882	0.722	3.316	2.425	4.611	0.496	4.745	2.856	3.149	2.159	3.03	1.948
	4.711	0.29	3.738	0.14	3.133	0.736	3.488	0.132	3.192	1.83	3.045	2.172
	4.8	0.274	4.586	0.31	3.844	0.199	3.607	0.897	3.137	2.17	3.197	1.59
sum	47.575	7.131	43.347	6.479	39.69	12.232	36.177	15.458	30.66	19.208	30.12	19.337
aveg	4.7575	0.7131	4.3347	0.6479	3.969	1.2232	3.6177	1.5458	3.066	1.9208	3.012	1.9337
sted	1.16	0.636	1.04	0.77	0.92	1.045	0.611	1.03	0.157	0.657	0.3162	0.71
var	1.33	0.402	1.097	0.598	0.8585	1.092	0.37	1.06	0.025	0.43	0.1	0.50

Table 1.6 ECT with deflection data

Appendix C: Tested Result of Box compression

	220/50(300X300X280			220/50/5(375X375x200)
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)	Dead weight Box compression After printing(Kg)
	911	93	13.8	100
	1145	117	20.21	100
	1110	113	13.17	95
	1256	128	39	90
	1059	108	17.26	95
sum	5166	559.3	104.51	480
avg	1096.2	112	20.902	96
sted	126	13	11	4
var	15947	125	124.9856667	17.5

Table 3.1 Experimental dada at AAIT ,BCTfor actual BCT (300*300*280)

	RS165/50(300X300X280)		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	761.5	78	1.7
	1224	125	22.35
	1148.6	117	2.6
	1316.2	134	3.289
	1143.7	117	14.942
sum	5594	571	45
aveg	1118.8	114	9
sted	212	22	9.2
var	44801.285	466	85

Table 3.2 Experimental data at unlimited, actual BCT (300*300*280

	RS220/80(300X300X280)		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	711	72.5	18.15
	833	85	20.21
	794	81	13.17
	883	90	13.8
	942	96	24
sum	3761.5	424	84.51
avg	752.3	**85**	17
sted	60	6.1	3.2
var	3581.2	37.21	10

3.3 Experimental BCT at RS220/80

	RS205/50		
	corrugated box sample size (300X300X150) mm		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	1866.9	190.3058104	19.368
	1745	177.8797146	32.383
sum	2936.9	368.185525	51.751
aveg	1468.45	184.0927625	25.8755
sted	563.4933939	8.786576618	9.202994757
var	317524.805	77.20392867	84.6951125
	corrugated box sample size (300X300X200) mm		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	1537.9	156.7686035	2.815
	1336.7	136.2589195	23.114
sum	2218.5	156.7686035	25.929
aveg	1109.25	156.7686035	12.9645
sted	163.6952198	156.7686035	14.35356055
var	26796.125	156.7686035	206.0247005
	corrugated box sample size(300X300X250) mm		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	1225	124.872579	3.663
	1047	106.7278287	8.614
sum	2272	231.6004077	12.277
aveg	1136	115.8002039	6.1385
sted	125.8650071	12.83027595	3.500885674
var	15842	1614.882773	12.2562005

	corrugated box sample size (300X300X300) mm		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	993.5	101.27421	11.293
	981	100	3.267
sum	1974.5	201.27421	14.56
aveg	987.25	100.637105	7.28
sted	1477.75	0.901002524	5.675239026
var	1480.875	0.811805549	32.208338
	corrugated box sample size (300X300X350) mm		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	914.5	93.22120285	2.818
	716	72.98674822	13.52
sum	9525.375	166.2079511	16.338
aveg	1190.671875	83.10397554	8.169
sted	415.2145795	14.30792009	7.567456772
var	172403.147	204.7165773	57.266402

Table 3.4 Experimental BCT at the same base at different height

	RS165/95(300X300X280)		
	Box compression (N)	Box compression (Kg)	deflection at first collapse(mm)
	993.5	101	11.293
	682.5	70	23.4
	936.2	95	13.123
	798.3	81	22.858
	561.1	57	11.949
sum	3971.6	405	82.623
aveg	794.32	81	17
sted	178	18	6
var	31678.4	329	37

3.6 Experimental BCT at RS165/95

Appendix D: Tested Result for mathematical relationship

	RS 165 /80		RS 185 /80		RS205/80		RS 220 /80	
	PAT (N)	ECT (N)	PAT (N)	ECT (N)	PAT (N)	ECT (N)	PAT (N)	ECT (N)
	333	410	307	401	208	285	298	381
	398	459	243	340	281	294	314	319
	300	395	280	411	224	296	346	410
	327	345	336	352	251	390	261	300
	314	365	395	435	355	405	274	341
	419	475	247	356	274	381	368	442
	320	400	352	394	262	300	259	290
	322	391	279	361	294	331	264	351
	332	500	280	380	310	411	300	310
	308	390	390	456	290	333	330	300
sum	3373	4130	3109	3886	2749	3426	3014	3444
avg	337.3	413	310.9	388.6	274.9	342.6	301.4	344.4
sted	39.212	49.4	55.06	37.97	42.27	49.65	38	51.6
var	1537.57	2441.33	3031.65	1442.26	1787	2465.15	1444	2661.6

Table 1.1 Experimental data for PAT and ECT at 80m/min.

	RS165/50		RS185/50		RS205/50		RS220/50	
	PAT(N)	ECT(N)	PAT(N)	ECT(N)	PAT(N)	ECT(N)	PAT(N)	ECT(N)
	396	500	470	498	390	438	400	488
	335	400	351	377	340	456	286	339
	328	443	336	430	360	442	368	484
	357	450	373	482	290	395	300	446
	345	466	313	370	360	434	376	473
	339	434	370	463	384	489	367	421
	363	449	360	390	286	320	315	410
	379	472	355	450	319	370	342	453
	330	376	376	455	345	498	333	460
	368	490	342	418	392	463	358	500
Sum	3593	3114	3646	3835	3466	4305	3445	4474
avg	359.3	444.86	364.6	426.11	346.6	430.5	344.5	447.4
sted	22.553	23.67	41.67	40.054	38.566	55	36.09	47.67
var	508.68	560.14	1736.5	1604.36	1487.378	3002	1302.72	2272.04

Table 1.2 Experimental data for PAT and ECT at 50 m/min.

	RS 165/80/5	Displacement (mm)	RS185/80/5	Displacement	RS205/80/5	Displacement	RS220/80/5	Displacement
	319	5	255	4.8	215	3.2	214	3.5
	337	5.2	292	5.2	248	4.7	286	5
	356	7	359	7	248	4	223	4
	351	6	261	5	257	5	277	5
	337	5.7	287	5.2	255	4.8	344	6
	306	5.4	316	8	300	5	268	4.5
	325	6	297	5	261	5.2	294	4.1
	318	4.5	310	6	321	6	305	5
	329	5.2	316	7	313	4.5	303	4.5
	360	9	327	6.5	310	5.5	293	4
avg	333.8	6	310	6.1	279.22	4.96	288.12	4.68
sum	3338	59	3045	59.7	2728	47.9	2807	45.6
stedv	17.75	1.286	33.053	1.103	35.496	0.78	38.59	0.72
var	315.3	1.65	1092.5	1.22	1259.95	0.608	1489.34	0.51

Table 1.3 Experimental data for PAT and deflection after printing

	FM RC at CD (KN/m)	Ft(mm)	F(gsm)	TL1 RC at CD (KN/m)	TL1t (mm)	TL1 (gsm)	TL2 RC at CD (KN/m)	TL2t (mm)	TL2 (gsm)
	0.95	Ft(mm)	137	1.31	0.2	138	1.2	0.23	143
	1.09	0.2	139	1.2	0.21	137	1	0.2	140
	0.85	0.19	131	1	0.19	135	0.9	0.2	129
	1.15	0.2	138	1.3	0.2	140	1.29	0.2	143
	1	0.2	137	0.9	0.21	129	1.34	0.2	143
	1.06	0.22	135	1.4	0.21	142	1.2	0.2	135
	1.1	0.22	138	0.85	0.21	134	1.16	0.22	133
	1.23	0.19	142	1.03	0.18	140	1.07	0.18	130
	0.91	0.2	140	1.14	0.2	136	1.1	0.22	135
	1.25	0.2	142	1.2	0.21	138	1.29	0.2	145
sum	10.59	0.22	1379	11.33	2.04	136.9	11.55	2.1	137.6
avg	1.059	2.05	137.9	1.133	0.204	136.9	1.155	0.21	137.6
sted	0.13	0.205	3.50	0.18	0.013	4	0.14	0.02	6.22
var	0.02	0.014	12.3	0.033		15.43	0.02	0.0003	38.8

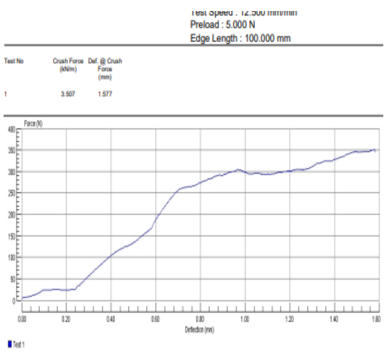
Table 1.4 experimental data for RC, paper grammage and thickness

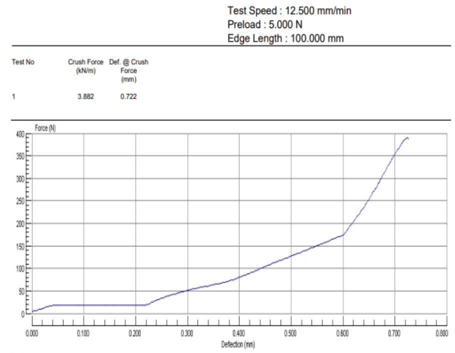
	RS220/50	t (mm)	RS185/80	t (mm)	RS165/95	t(mm)	RS205/80	t (mm)
	4.55	4.09	3.96	4.05	4	4.1	3.88	4.13
	4.96	4.13	3.35	4.04	3.59	3.9	3	4
	4.27	4.06	4.16	4.09	4.21	4	4	3.9
	4.35	4.1	3.42	4.08	3.37	4.03	3.19	4
	4.46	4.1	3.9	4.1	4.11	3.97	3.23	3.98
	4.52	3.9	3.63	4	3.48	4.02	3.63	4.11
	4.7	4.1	4.1	4.04	4.44	4.02	3.32	3.95
	4.67	4	4.56	4.07	4.31	4	3.76	4.05
	4.73	4.18	3.84	4.08	3.4	4.03	3.41	3.98
	4.84	4.03	4	4	3.97	4.05	3.5	4
Sum	46.05	40.69	38.92	40.55	38.88	40.12	34.92	40.1
avg	4.605	4.069	3.892	4.055	3.888	4.012	3.492	4.01
stedv	0.21	0.077	0.36	0.035	0.4	0.05	0.32	0.07
var	0.046	0.006	0.13	0.0012	0.16	0.003	0.10	0.005

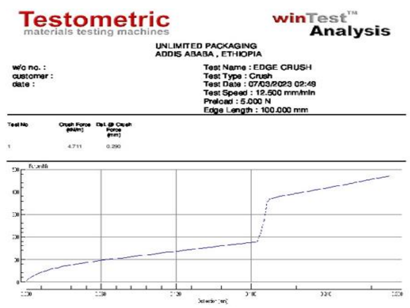
Table 1.5 ECT vs board thickness

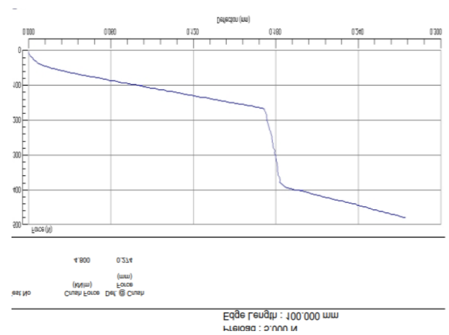
Appendix 1: Tested ECT at first crushed deflection graph

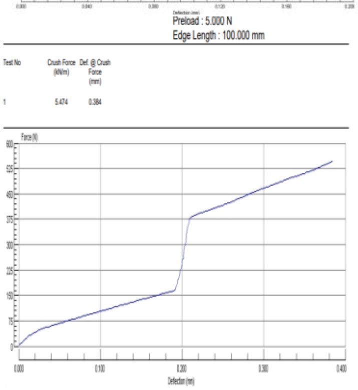
1.1 RS220/50 ECT at the fist crush force deflection

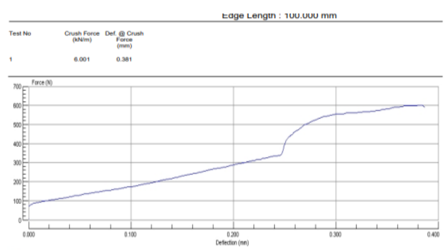


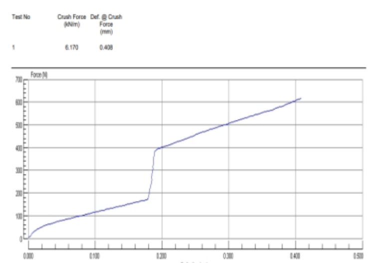


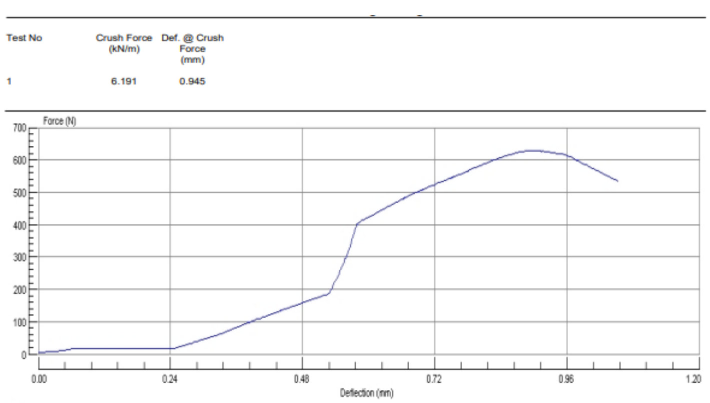




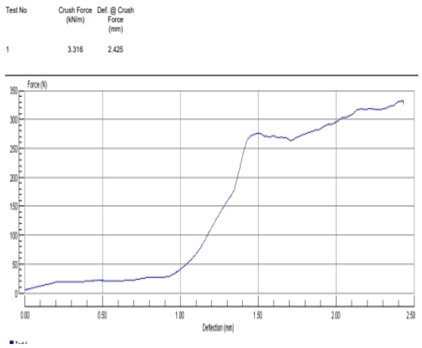


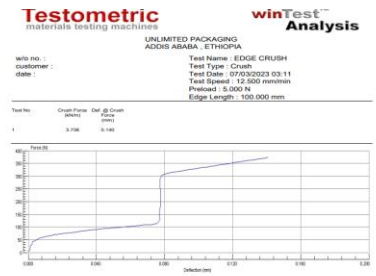


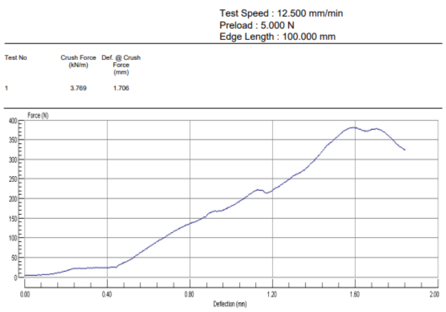


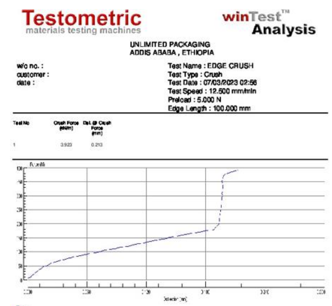


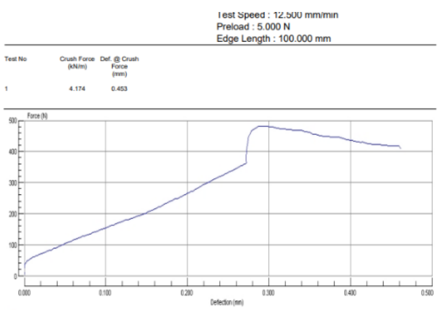
1.2 RS165/65 ECT at the first crush force deflection

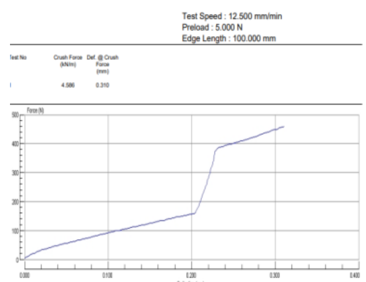


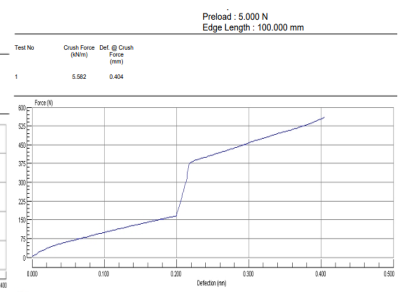


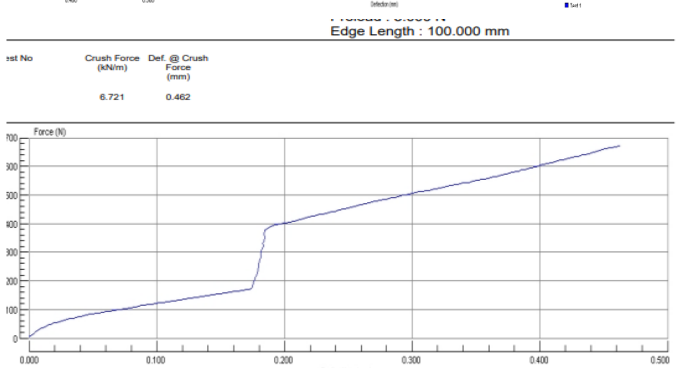




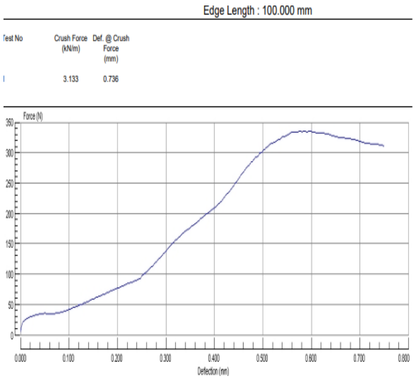


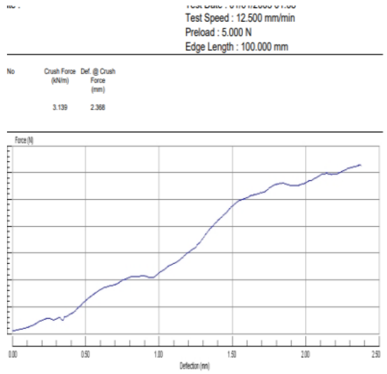


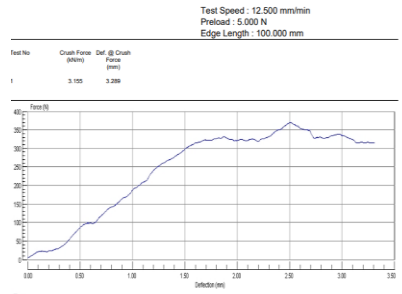


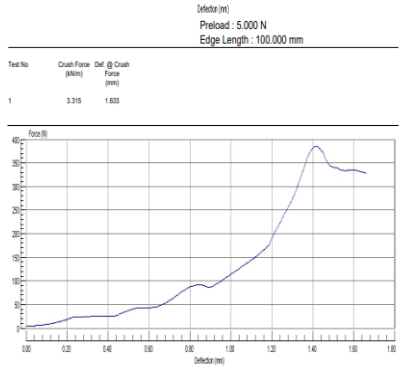


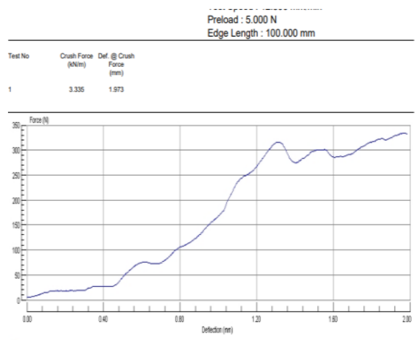
1.3 RS185/80 ECT at the fist crush force deflection

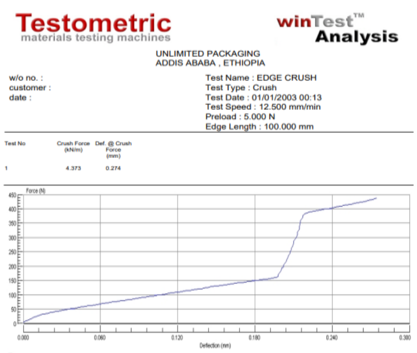


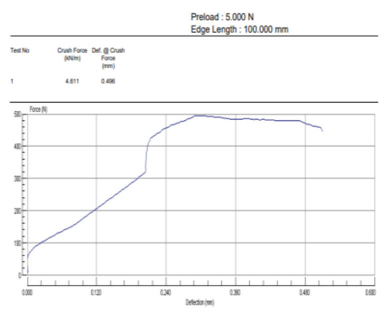


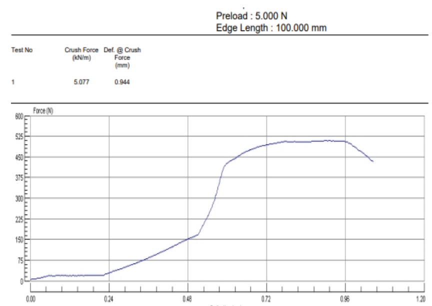


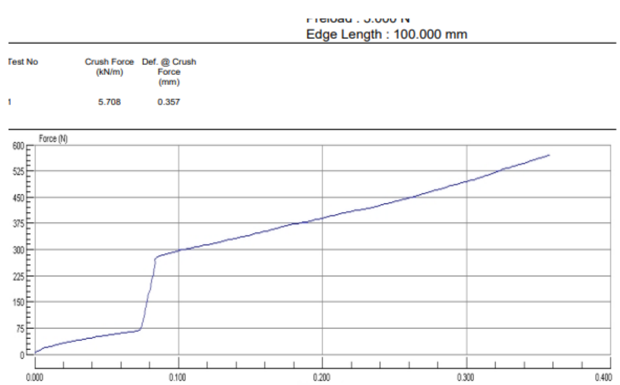




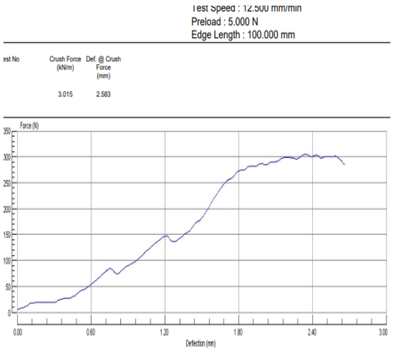


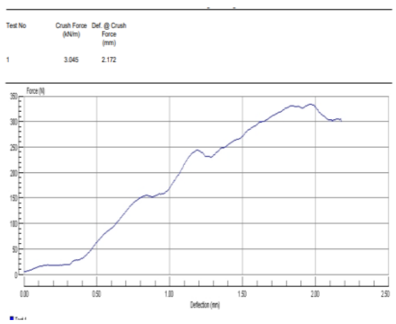


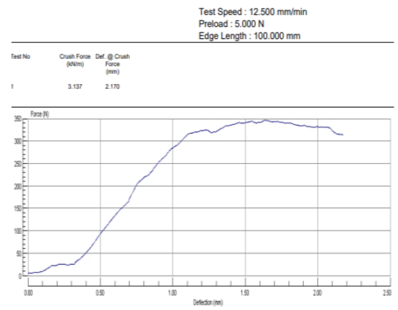


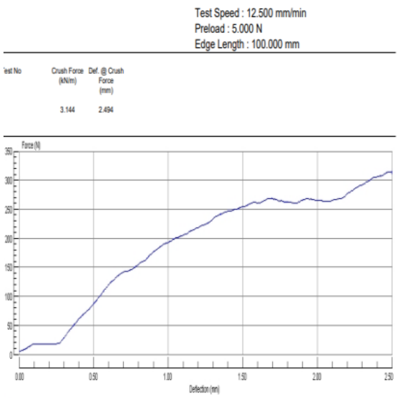


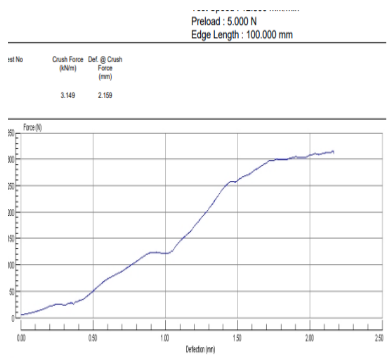
1.4 RS185/95ECT at the fist crush force deflection

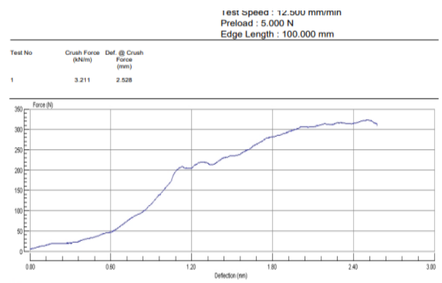


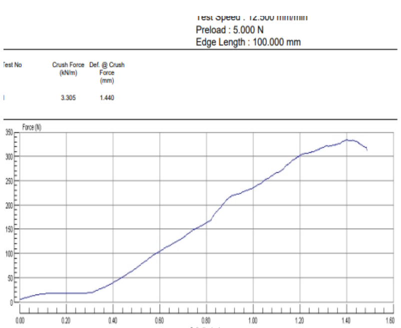


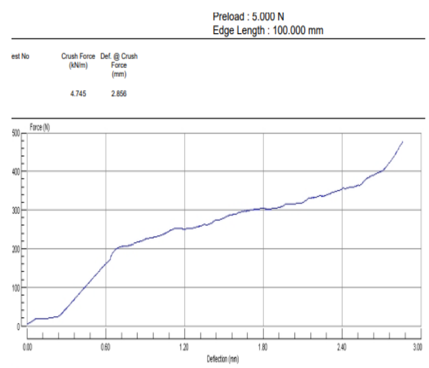


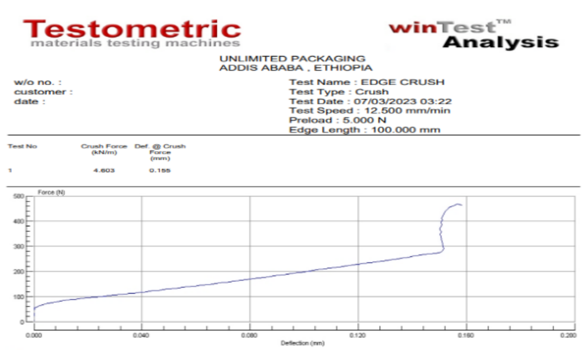




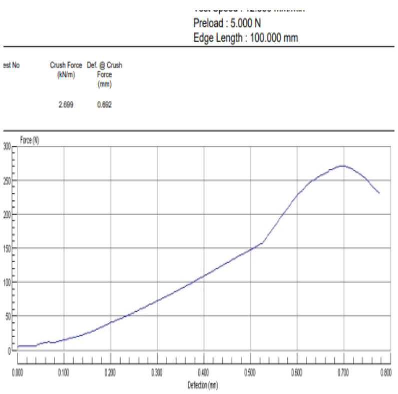


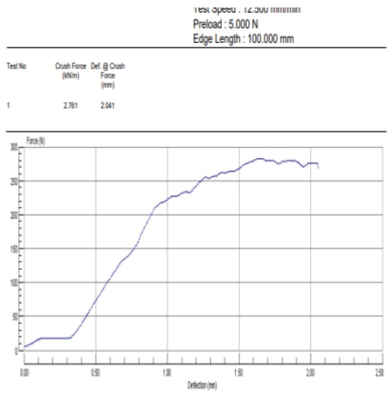


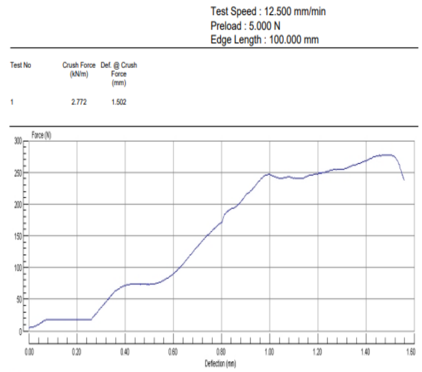


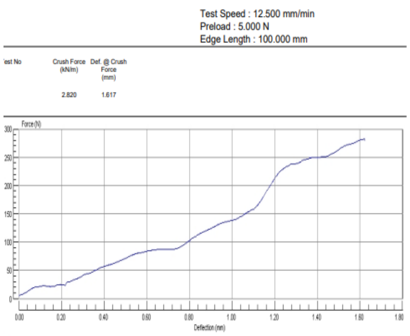


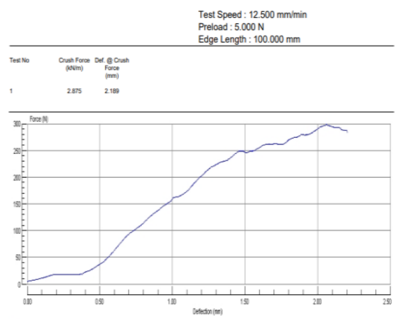
1.5 RS205/95 ECT at the fist crush force deflection

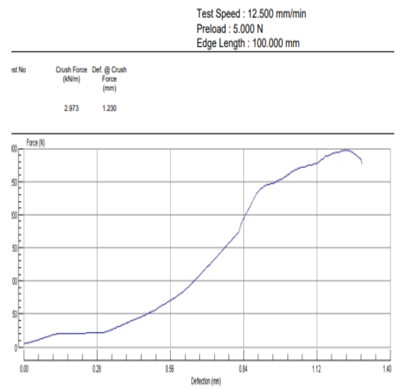


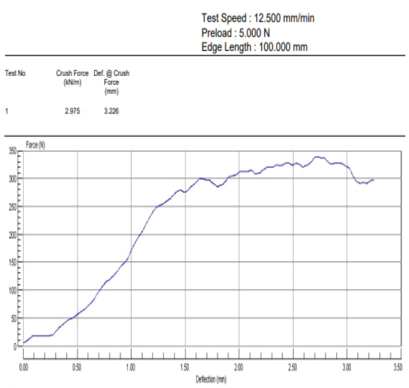


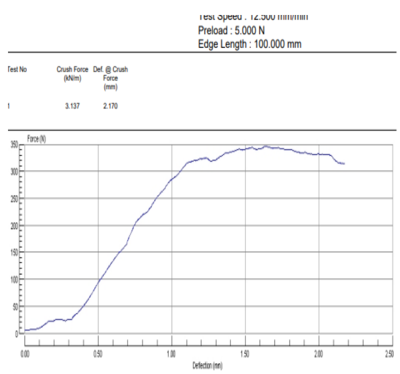


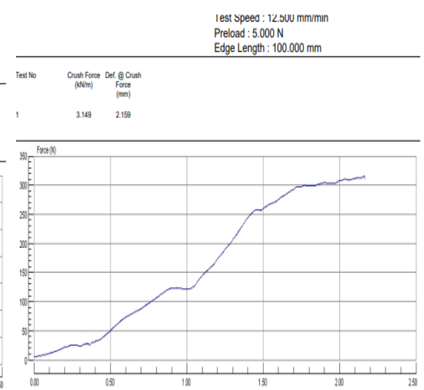


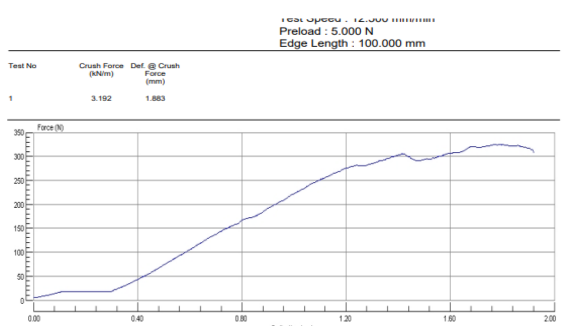




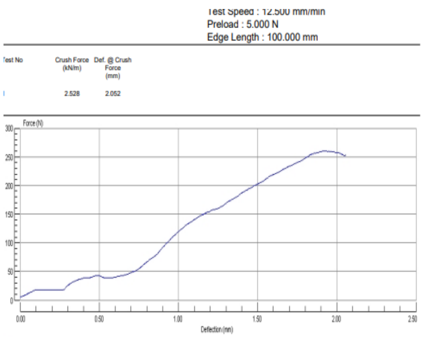


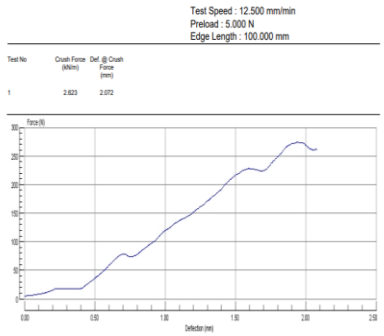


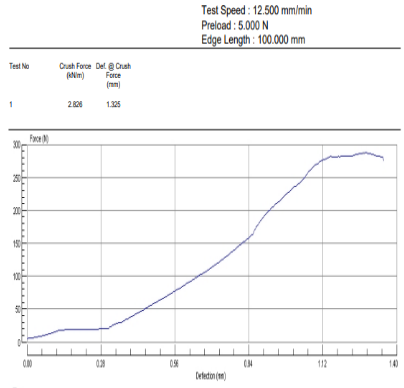


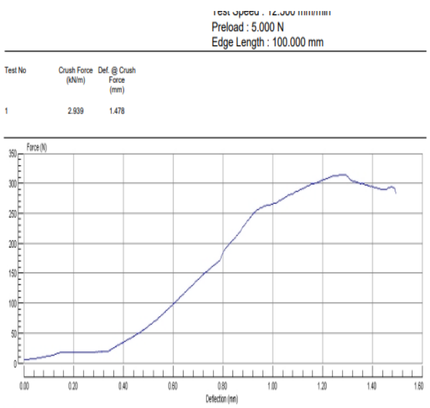


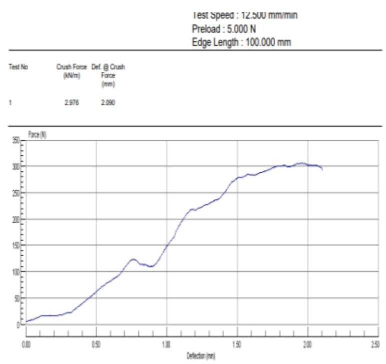
1.6 RS220/95 ECT at the fist crush force deflection

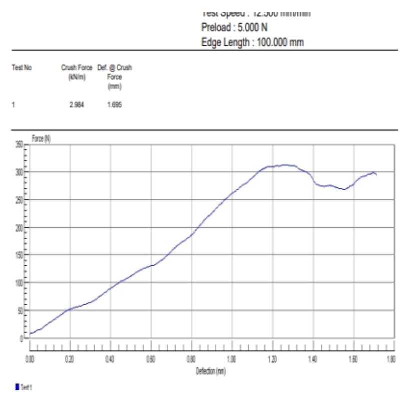


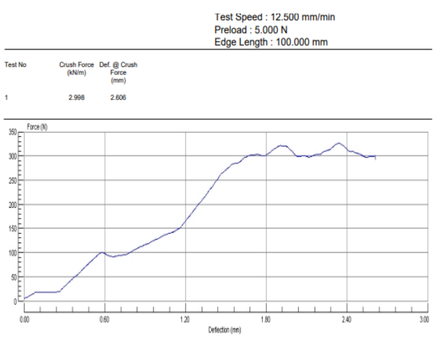


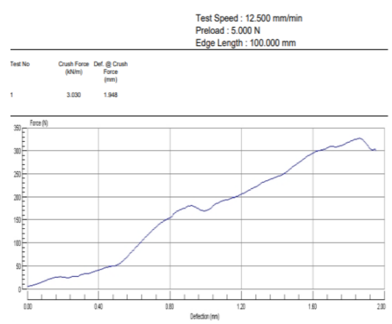


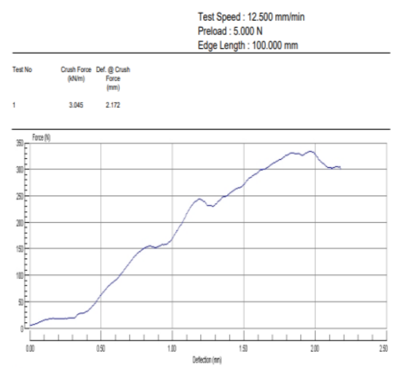


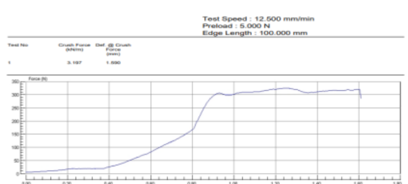






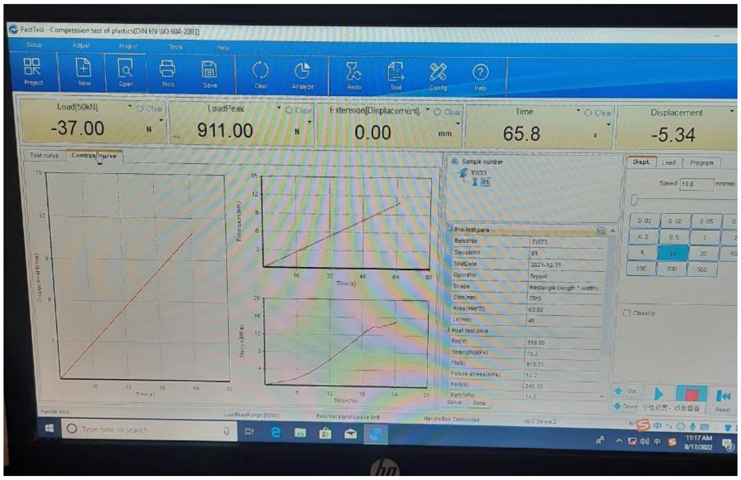




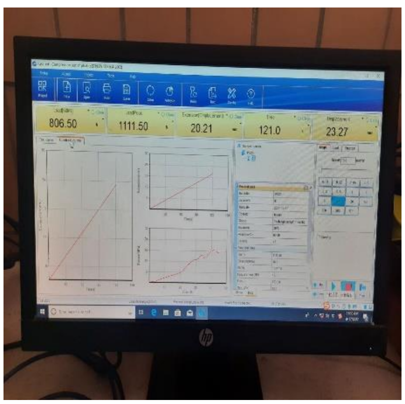


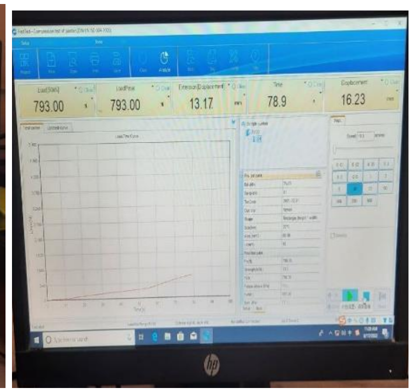
Appendix 2: Tested corrugated box at different FS and RS

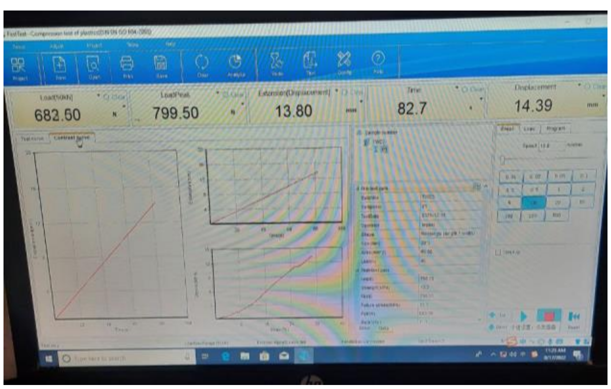
2.1.RS220/50



2.2 RS165/95

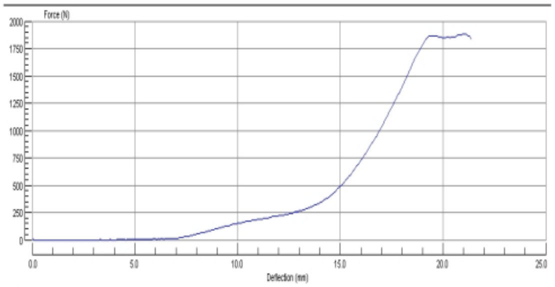




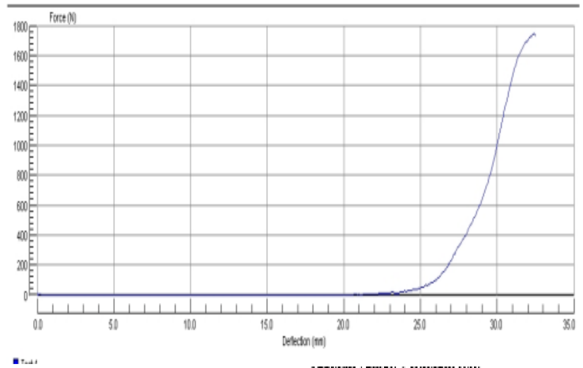


2.3 RS205/50 (300*300*150)

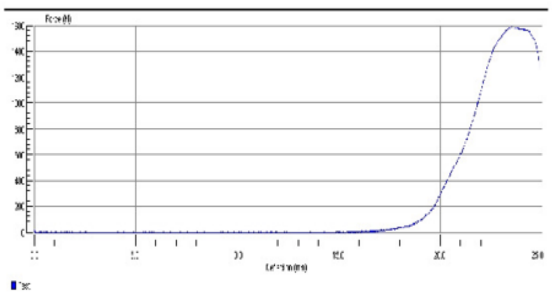
Test No	Force @ 1st Collapse (N)	Def. @ 1st Collapse (mm)
1	1866.900	19.368



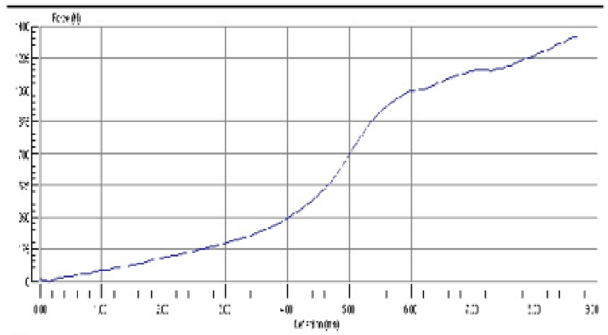
Test No	Force @ 1st Collapse (N)	Def. @ 1st Collapse (mm)
1	1745.400	32.383



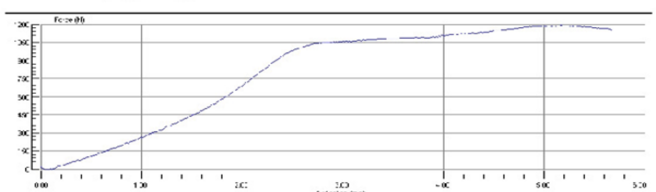
Test No	Force @ 1st Collapse (N)	Def. @ 1st Collapse (mm)
1	1537.900	23.114

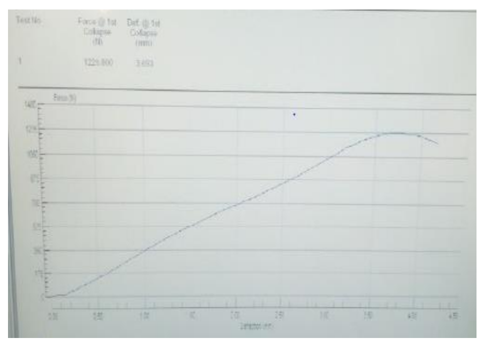


Test No	Force @ 1st Collapse (N)	Def. @ 1st Collapse (mm)
1	1336.700	8.614

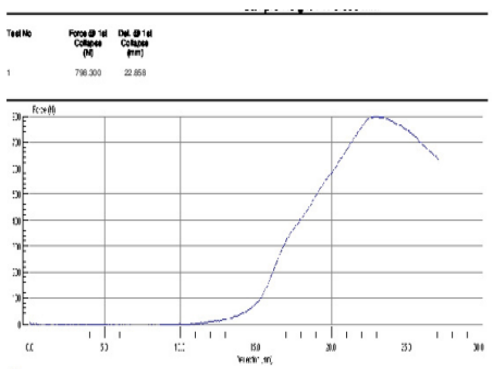


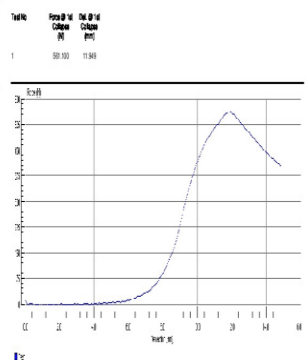
Test No	Force @ 1st Collapse (N)	Def. @ 1st Collapse (mm)
1	1047.000	2.815

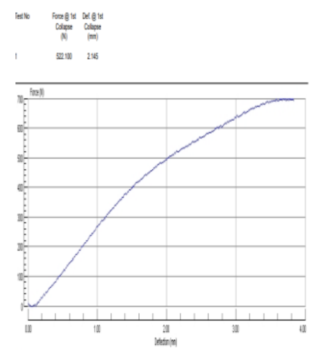




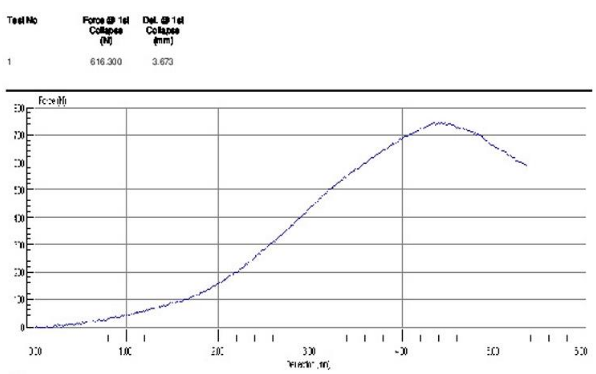
2.4 RS205/85

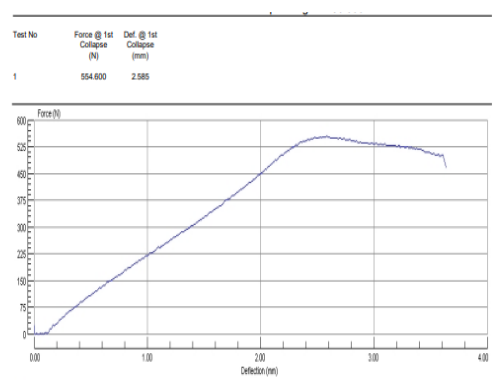


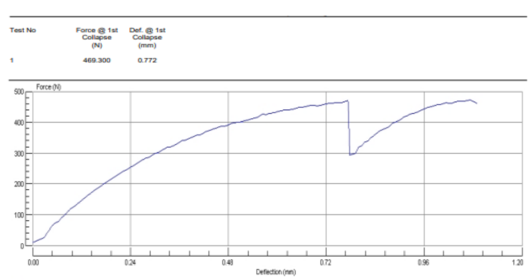


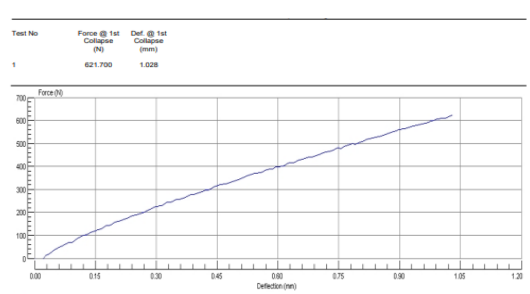


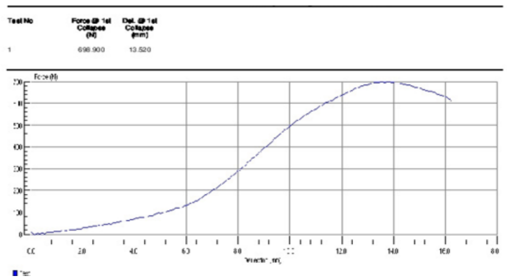
2.5 RS185/95



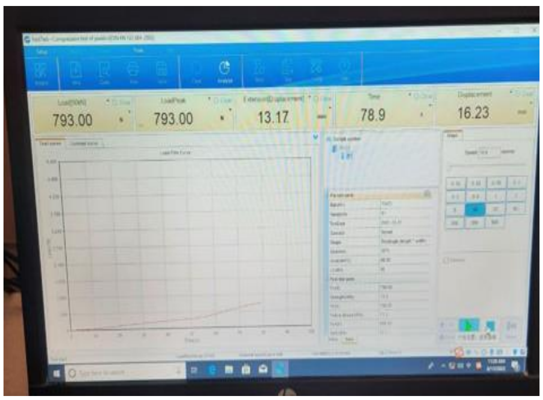


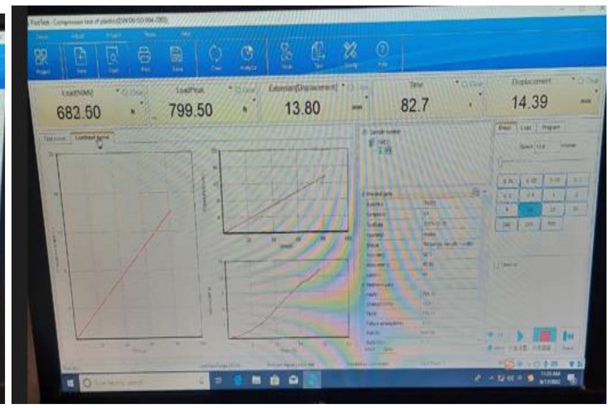





Test No
Force @ 1st Collapse (N)
Def. @ 1st Collapse (mm)
1
698.900
13.520
Force (N)

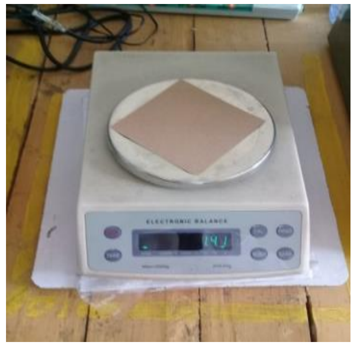
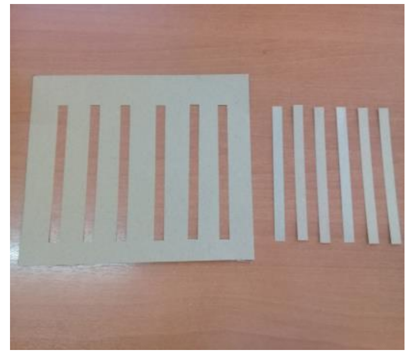
2.6 RS220/80


793.00
793.00
13.17
78.9
16.23


682.50
799.50
13.80
82.7
14.39

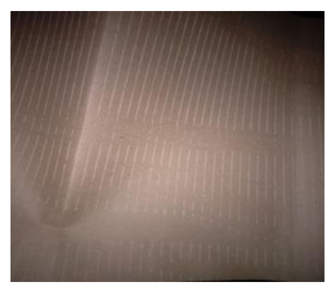

Width : 258.000 mm
Breadth : 338.000 mm
Sample Height : 146.000 mm
Test No
Force @ 1st Collapse (N)
Def. @ 1st Collapse (mm)
1
793.500
11.295

Appendix 3: Apparatus available at BPPI for the experimental work on Material Property Test

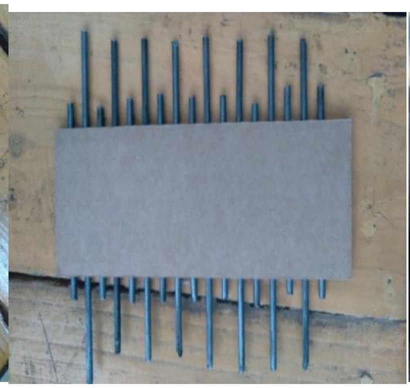
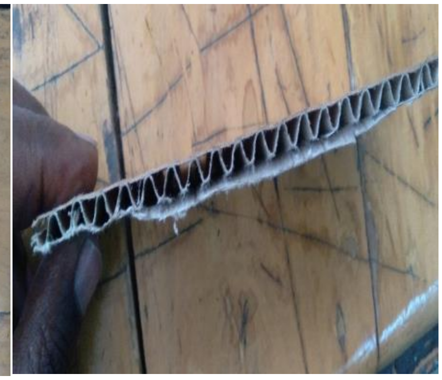






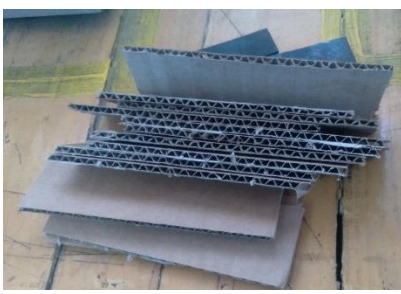


Appendix 4: Apparatus available at BPPI for the experimental work on PAT






Appendix 5: Apparatus available at Burayu and Unlimited packaging industry for the experimental work on ECT

Appendix 6: Apparatus available at AAIT and unlimited packaging industry for the experimental work on CBT