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A
SEMINAR REPORT
ON

TO INVESTIGATE THE EFFECT OF USING DRY DEFIBRATED FIBERS IN INCREASING BULK AND BENDING STIFFNESS OF THE MULTI-PLY PAPERBOARD.

Submitted in partial fulfillment of the requirement for the award of degree of

MASTER OF TECHNOLOGY

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this Dissertation report entitled **"To investigate the effect of using dry defibrated fibres in increasing bulk and bending stiffness of the multi-ply paperboard"** in partial fulfillment of the requirement for the award of the degree of Master of Technology (Packaging Technology) and submitted in the Department of Paper Technology, IIT Roorkee, Saharanpur campus is a record of my own work carried out, under the supervision of Associate Prof. Dr. Chhaya Sharma, Prof. Dr.-Ing André Wagenführ and Dipl.-Ing Thomas Schrinner.

The matter embodied in this project report has not been submitted by me for the award of any other degree of this or any other Institute. I have given due credit to the work whichever I have used in this report.

Date: 16-5-2019

Place: Saharanpur

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This is certified that the above statement made by the candidate is correct to best of my knowledge.

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ABSTRACT

Aim of the work is a simultaneous improvement of the production process and of properties in multilayer board production by application of dry defibrated fibre materials, especially in the middle layer.

Background of the project idea are the characteristic properties of dry defibrated fibre materials, enabling an essentially faster dewatering compared to conventionally wet defibrated fibres. Furthermore, the use of dry fibres results in significantly higher sheet thicknesses. Especially this potential for increasing the specific volume is conform to development targets of board manufacturers.

The planned investigations are focusing on dry defibration of several recovered papers and the subsequent application of these materials in the middle layer of a three-layer laboratory model board. By replacing wet defibrated material with dry defibrated fibres increased drainage rate, sheet thickness and a higher bending stiffness is expected compared to the reference board from completely wet defibrated raw material.

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CHAPTER 1 | INTRODUCTION

1.1 PAPERBOARD:-

Paperboard can be loosely defined as “stiff and thick paper” .The distinction between paper and paperboard is based on product thickness. Nominally, all sheets above 0.3 mm thickness are classed as paperboard ; but enough exceptions are applied to make the distinction somewhat hazy. The line of demarcation between paper and paperboard is somewhat vague, but has been set by the I.S.O. at a grammage of 224g/m^2. Therefore, materials above 224 g/m^2 is termed board while lighter weights fall into the category of paper [1]. Common raw materials for the manufacture of paperboard are wood pulp, straw and waste paper, or a combination of these material . It is an interlaced network of cellulosic fibers. Fibers which are directly derived from wood are known as primary or virgin fibers and the fibers which are derived from used paper and paperboard are known as secondary or recycled fibers. Paperboard is composed of renewable raw materials and it has many favorable properties so that it can be used in graphical and packaging applications. Paperboard can be made in single layered or multi layered. Several layers of fibers are joined together in wet state to get multi layered paperboard[2]. The advantage of the multi ply board is that each layer gives ability to optimize fibers characteristics to give certain functionality to the paperboard. To fully utilize the potential of optimizing characteristics in the paperboard it is necessary that multi ply construction contains at least three plies. Presence of thicker middle ply and strong outer plies provides necessary stiffness to the paperboard.

1.2 PAPERBOARD IN PACKAGING:-

Protection of the product is primary paperboard function in packaging applications. Paperboard should be able to withstand range of applied stresses during printing, converting, packaging and distribution.

Exposure to very humid conditions results in increase moisture content and reduction in strength properties. Paperboard should have good toughness and strength to withstand stresses that are applied to it during packaging operations. Toughness and strength of the paperboard are complex properties which are defined by characteristics like elasticity, elongation, stiffness, tensile strength. Due to paperboard’s small volume and low weight, a large amount of energy is saved in package transportation. Paperboard can be divided into four different types namely:-

i. SBB, Solid Bleached Board
ii. SUB, Solid Unbleached Board
iii. FBB, Folding Box Board

iv. WLC, White Line Chipboard

Virgin fibers is advantageous over recycled fibers because virgin fibers retain much of their original strength. Paperboard made from virgin fibers is more stronger and gives better performance in printing converting and use. Recycled materials are widely used in the manufacture of packaging products, This can be primarily due to the fact that Virgin fibers can often be more expensive than fibers obtained from recycled materials[3].

SBB, SUB and FBB are made from virgin fibers and WLC is made from the recycled fibers. For a paperboard to be used as a packaging material it must:-

i. Fulfill the functional demands of the product i.e protection of the product and prevention from its wastage.
ii. Paperboard should be durable and practical enough in distribution and handling and also in end term consumer use.
iii. It should also provide a means for the product promotion.
iv. Contributes to the total economy of the product
v. Be adequate from an ecological point of view.

1.3 MULTI-PLY PAPERBOARD:-

Paperboard can be made in single ply or more commonly in several plies or we can say multiply construction. In practice refining is used to modify elastic modulus, but thickness is modified by using bulky raw materials. To combine these two different strategies in paperboard, multiply structure has been suggested[4]. For fully utilizing the potential of optimizing characteristics in the paperboard it is crucial that multi-ply construction consists of at least three layers.

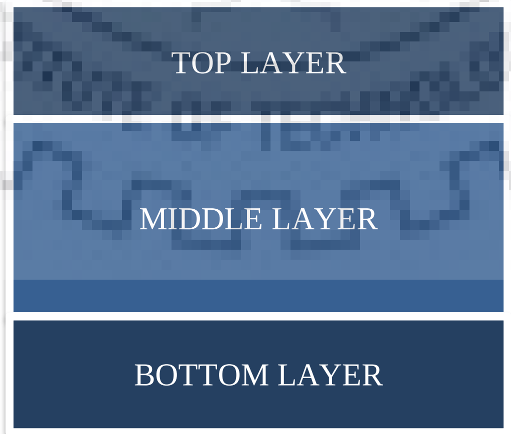


Figure 1 : Cross Section of a three layered paperboard

The advantages of the multi layered construction of the paperboard lies in the ability to optimize fiber characteristics in each layer to get certain functionalities. This can be done by following methods.

i. Proportionating short and long fibers in respective layers.
ii. Type of pulping method used for fibers to be used in respective layers.
iii. Treating pulp to improve bulk or strength quality.

The middle ply in the paperboard enables the paperboard maker to optimize surface characteristics in the outer layers without loss in stiffness and converting advantages which are provided by the middle ply. Features which are easier to optimize in a multi-layer construction than in a single layer construction without compromising are listed below:-

i. Bulk
ii. Strength
iii. Stiffness by higher thickness and strong outer plies.
iv. Surface smoothness with desired stiffness and strength
v. Desired functional features in each layer separately such as moisture resistance etc.

Refining is used to modify elastic modulus practically but thickness is modified using bulky raw materials. For combining these two different strategies in paperboard, multiply model has been suggested. Chemical pulp is higher in elasticity therefore it is used for surface layers and bulky mechanical pulp is used in middle layers[3]

1.4 DRY DEFIBRATION TECHNOLOGY:-

Dresden University of Technology has developed a new process aiming at pulping recovered paper and board products without water. This dry fiber preparation technology has already been tested on pilot scale with promising results. The fibers produced by this pulping method are known as dry fibers. The technology favors pulping of difficult to recycle products with only 75 kwh/t of specific energy demand as compared to wet defibration in which specific energy demand can easily rise up to 300 kwh/t also common grades of recovered paper can be defibrated sufficiently by dry defibration though with limited advantages in terms of energy efficiency and quality[4]. The fibers produced by dry defibration have the potential to increase the sheet properties of selected paper and board products. Compared to wet pulped material the use of dry-pulped fibres enables an essentially faster dewatering and furthermore results in significantly higher sheet thicknesses.

1.5 OBJECTIVE:-

Now our objective is to use dry defibrated fibers materials in the middle layer of the multilayered paperboard for the improvement of production process and of properties of the multilayered board like thickness, bulk and bending stiffness. The background of this work is that in previous studies it was found that dry fibers increase the specific volume (bulk) of a paper or board and because bulk is very important property for packaging materials, it should be examined in this work if dry pulping and the use of dry fibers offers the possibility to improve both bulk and stiffness.

CHAPTER 2 | LITERATURE REVIEW

2.1 PRODUCTION OF DRY FIBERS:-

Dry defibrated fibres can be produced by dry and purely mechanical defibration of recovered paper. The process concept is based on the principle of a mechanical airflow impact mill. In this process the product to be comminuted is fed to the bottom of the mill via an air flow. The product is pre-crushed by beaters and then moved into the inner periphery of the mill. The high rotor and air velocities and the design of the grinding elements generate highly turbulent micro vortices which induce intense secondary comminution processes due to the particles crashing into each other and due to friction and shearing forces[4].

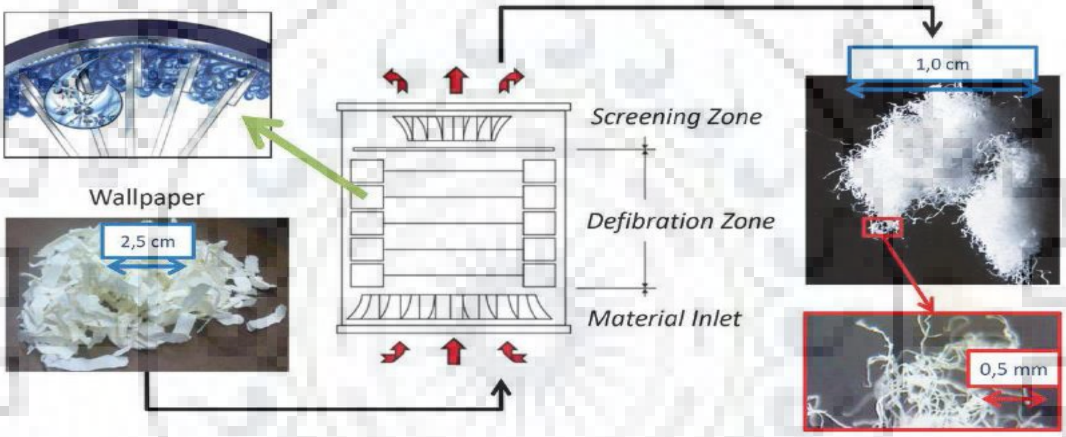


Figure 2 : Schematic illustration of dry defibration including material inlet and product output[5].

2.1.1 Acting Forces:-

i. Impact forces between particles within a rotating turbulent flow.
ii. Impact forces between particles and grinding elements
iii. Compression and shear stresses in the gap between the grinding elements and the inner surface of the stator
iv. Stresses within the turbulent air flow.

2.2 TYPES OF PULP:-

In general there are three kinds of pulping processes which produces three different kinds of pulps i.e mechanical, chemical and recycled fiber. They are discussed in brief as follows:-

2.2.1 Mechanical Pulp:-

Mechanical pulp are commonly produced from softwood species. Due to presence of lignin in the pulp the fibres are hard and rigid. This gives paperboard high stiffness but limited strength, low density and lower resilience. Virgin fiber pulp containing lignin due to mechanical separation reacts more strongly to changes in external environment, humidity and temperature, a reaction that affects the flatness and dimensional stability of paperboard. Resulting paperboard made solely from mechanical pulp is relatively weak. The paperboard made from mechanical pulped fibers retains yellowish color of the wood used.

Figure 3 : Mechanical pulp[2]

2.2.2 Chemical Pulp:-

Length of the virgin fibers is preserved in this process. Pure cellulose is extracted without lignin in this process which produces a very strong paperboard sheet. The fiber produced is more flexible and soft then mechanical pulped fibers hence giving good creasing, embossing and die-cutting properties. Bleached cellulose pulp has more brightness, whiteness and pulp stability. Paperboard made from chemical pulped fibers has highest purity and provides packaged food with best taste and odour protection.

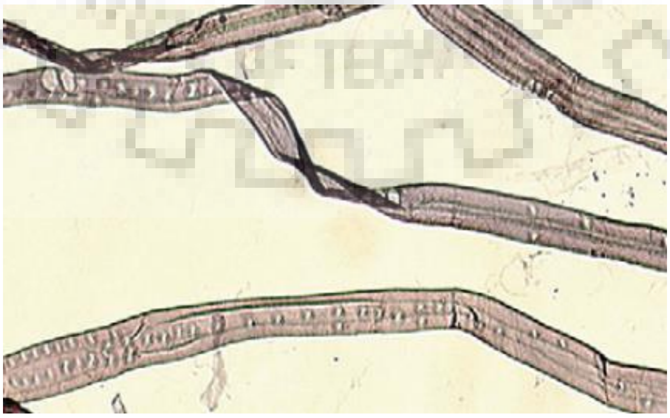


Figure 4 : Chemical pulp[2]

2.2.3 Recycled Fibers:-

This process utilizes a wide variety of waste paper and board. Whenever a fiber is recycled it is contaminated and its length is shortened. Virgin fiber must be added to the recycled pulp to maintain the quality of the recycled pulp. Mixed paper waste is not usually de-inked for paperboard manufacture and hence the pulp has traces of ink, adhesives and residue which results in grey coloration of the paperboard. The resulting product from recycled fibers has poorer functional properties than virgin fiber based boards.

2.3 IMPORTANCE OF BENDING STIFFNESS FOR PAPERBOARDS:-

Bending stiffness is regarded as one of the most critical property for paperboards. After grammage and thickness, stiffness is the next most important property that a paperboard specifier usually considers when choosing paperboard. Packaging boards require higher bending stiffness for a good runnabilty and higher strength to resist bending. Bending Stiffness depends on both the thickness as well as elastic modulus of each layer of the multilayered paperboard. Bending Stiffness can be improved through modification in elastic modulus, the bulk of the mid ply and grammage distribution among the layers of the paperboard. The mid ply bulk and grammage distribution among layers can play a significant role in improving bending stiffness of the multi-ply paperboards.[6]. Stiffness is particularly important when determining the correct grade of paperboard for packaging applications .It is stiffness that enables paperboard to be used for a wide range of packaging and graphical applications .Without stiffness paperboard would not be able to perform its primary function of providing the packaged contents with physical protection. Stiffness itself also relates to other strength properties such as compression strength, toughness, creasability, foldability, etc.

2.4 EVALUATION OF BENDING STIFFNESS:-

For homogeneous beam of constant thickness and modulus of elasticity in the plane of paper or board, the bending stiffness can be derived from the following equation[7]:-

$$S_b = \frac{E \times I}{b}$$

Where, S_b = Bending Stiffness per unit width b

E = Modulus of elasticity

I = Second moment of inertia

b = sample thickness

2.4.1 Two Point Bending Method[7]:-

This method is suitable for paperboard with low thickness. It can be performed in two ways.
In first method the beam is clamped to one end and subjected to a force F in the starting of the test acting perpendicular to the surface of the plane at a bending length "l" from the clamp. The linear deflection "f" of the test piece is the shift in the point of the application of the force in the direction where it is acting[7].

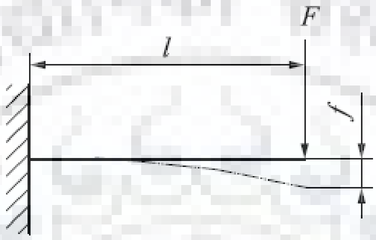


Figure 5 : Two Point Bending Method with linear deflection,f[7]

If the bending force "F" and the linear deflection "f" are measured during the bending test, the bending stiffness "S_b" can be calculated by following equation:-

$$S_b = \frac{F}{f} \times \frac{l^3}{3b}$$

If bending angle, α which is the angle through which the clamp is rotated while performing the test is given, then bending stiffness can be calculated by the following equation:-

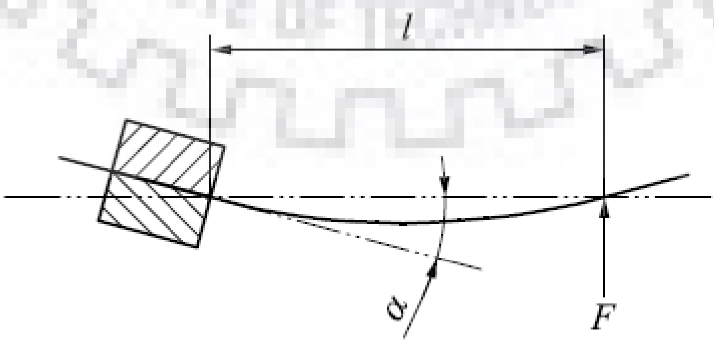


Figure 6 : Two Point Bending Method with bending angle,α[7]

$$S_b = \frac{60}{\pi} \times \frac{F}{\alpha} \times \frac{l^2}{b}$$

It is assumed that bending occurs with negligible inter-laminar shear strain for the above equations and the test piece also should not suffer any permanent deformations during the bending test.

2.5 METHODS TO INCREASE BULK AND BENDING STIFFNESS OF PAPERBOARDS:-

2.5.1 Combining Stiff Fibers And Extremely Refined Fibers:-

The combination of stiff fibres and extremely refined fibres produced higher stiffness at the same tensile strength than the control finish, in which all the fibres are refined together. The stiff fibres, which were mechanically not treated or treated slightly to remove fibre curls were combined with extremely refined fibres (ERF) to produce higher stiffness papers than those where whole fibres were refined. ERF was used as bonding agent and the stiff fibres are used as structure elements to keep the paper thickness[8]. By making the paper such a way, we could keep the breaking length at the same basis weight, but at higher thickness, which in turn generates higher stiffness.

2.5.2 Using Mechanical And Chemi-Mechanical Pulps:-

Mechanical and chemi-mechanical pulps are most efficiently used in plies, for which it is worth striving for a high bulk, e.g. in the center ply in three-ply sheets. The most important purpose for mechanical or chemi-mechanical pulps in furnishes that form such a ply is to create a high distance between the outer layers. Such a composite will thus achieve an enhanced bending stiffness as compared to homogenous sheets, when the bulky middle ply is combined with strong top and reverse plies with a high tensile stiffness[8]. An obvious prerequisite in relation to achieving a high bending stiffness is that the internal fibre-fibre bond strength is sufficiently high to prevent splits in the porous middle ply during the converting processes.

CHAPTER 3 | METHODOLOGY

3.1 PROCESS FLOW SHEET:-

Following diagram shows the schematic process of preparing single layer handsheets or multilayered paperboards.

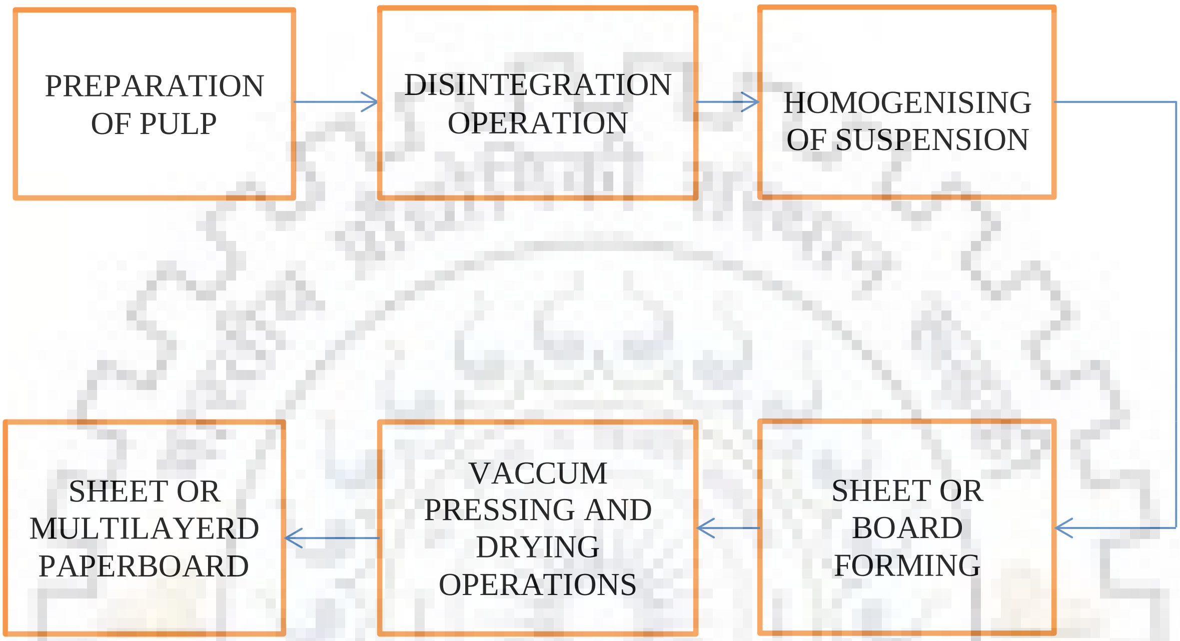


Figure 7 : Process Flow Sheet

3.1.1 Preparation Of Pulp :-

For the production of single layer hand sheets of 80 gsm made from dry fibers, 30 g dry fibers were taken in a1000 ml beaker and then they were soaked in water for fibers to swell up for the ease of further operations for almost 16 hours. For disintegration to take place easily the strength of the paper must be overcome by wetting operation for the breakage hydrogen bonds and fiber swelling due to interaction between water molecules and fibers[16] . For single layer hand sheets of 80 gsm made from wet pulped material , recovered paper was comminuted into 2*2 cm of pieces by hand to make 30g of material and then taken into a 1000 ml beaker and then it was also soaked up for 16 hours for the fibers to swell up for the ease of further disintegration operations.

3.1.2 Disintegration Operations :-

In disintegration operations, in most of the trials performed dry fibers were not disintegrated and used as such. For Conventional wet defibration, material was disintegrated in a disintegrator which was running at 3000 rpm for the duration of 10 min. For disintegration we added 1000 ml more water to the already prepared sample of 1000ml .So disintegrator was operating at 2000ml of water and added comminuted recovered paper material.

Figure 8 : A disintegrator

3.1.3 Dilution And Stirring Operations :-

After disintegration the conventional wet defibrated pulp and dry defibrated pulp was added to homogenizer to maintain consistency and homogeneity of the solution by continuous stirring operations.

Figure 9 : A homogeniser

In most trials performed 30 g of dry fibers were diluted to 9000ml of water and then stirred continuously for maintaining homogeneity and consistency level of 0.33 %.

Similarly 60g of wet defibrated materials was diluted to 14000 ml of water to and then stirred continuously for maintaining homogeneity of the pulp suspesion and consistency level of 0.42%. The stirring operations were allowed to continue for 2 minutes before they can be used to make test sheets to determine the amount of pulp solution required to produce a sheet of specific grammage or mass.

3.1.4 Sheet Or Board Forming :-

A sheet former was used in which several operations occur simultaneously such as filling, bubbling, settling and drainage.

Firstly test sheets were prepared for both the materials which are to be used by taking 500 ml of both the pulp solutions and then making sheets of them to check the mass of the sheets produced. And then to make handsheets of specific grammage and mass, pulp solutions were taken accordingly to the reference test sheets.

For producing paperboards multilayered sheets were combined by pressing on top of each other. 3 layered and 5 layered paperboards were generally produced in this handsheet maker.

In multilayered paperboard making sheets were gently aligned on top of each other, one after another so that a perfectly aligned paperboard to be produced. After that hansheet or paperboard formed was further placed into the next step for pressing and drying operations.

Figure 10 : A handsheet maker

3.1.5 Vacuum Pressing And Drying Operations :-

After formation of handsheet or paperboard in the handsheet maker, they were further placed into pressing and drying section for 10 minutes and at a temperature of 94°C . After drying and pressing by applying heat and vaccum, the weight of the sheet is measured twice again after another drying and pressing operation at a interval of 3-4 minutes to check whether the sheet or board is dried to optimum amount and the weight of the sheet that we are obtaining is almost constant.

Figure 11 : Vaccum pressing and drying operation

3.1.6 Sheet Or Multilayer Paperboard :-

Finally after going carefully through all of the above mentioned steps we get paperboard or handsheet of specific mass or grammage. 5 different samples of each composition were produced while performing the trials. The samples prepared were placed in climate room after formation at 23 degree Celsius and 50% relative humidity for a period of 24 hours so that the sheets or paperboards formed can come to standard conditions for testing.

3.2 TESTING OF PROPERTIES:-

After being placed in the climate room for almost 24 hours the following mechanical properties of the handsheets were tested

i. Grammage
ii. Thickness
iii. Bulk
iv. Tensile Strength
v. Bending Stiffness
vi. Scott bond or internal bond strength.

3.2.1 Grammage :-

Grammage of paper or paperboard the mass per unit area of handsheet or multilayered paperboard formed. It can also be represented by the symbol “GSM” or in metric systems by grams per metre square (g/m^2)[9] .

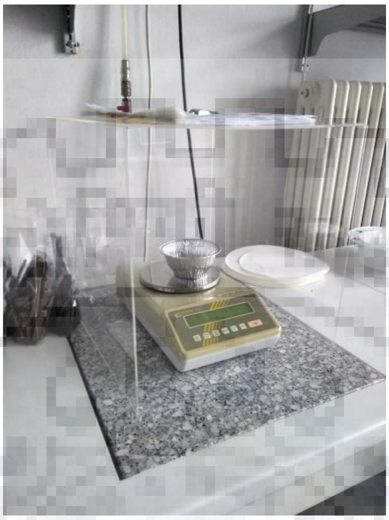


Figure 12 : Weighing balance to measure grammage

A test specimen of handsheet or multilayered paperboard is placed on top of the aluminium cup for the accurate measurement of the mass of the sheet or paperboard. The instrument is tare to the value zero after placing aluminium cup on it. The cup provides optimum area for placement of handsheet or paperboard on top of it. After measuring mass, the following equation is used to calculate grammage of the handsheets produced.

$$grammage\ (\frac{g}{m^2}) = \frac{mass\ of\ the\ handsheet\ formed\ (g)}{area\ of\ the\ handsheet\ formed\ \ (m^2)}$$

3.2.2 Thickness :-

Thickness can be defined as the perpendicular distance between the two principal surfaces of the paper or paperboard under prescribed conditions, as measured between hard metal platens[10]. Thickness plays important role in calculating bulk of the paper or paperboard. Thickness is also measured at different places on the same handsheet formed to check whether the sheet formed is homogeneous or not.

Figure 13 : A micrometer.

The specimen was placed between the two metal clamps of the micrometer in the open position and then the movable clamp approaches the stationary base metal clamp to take the measurement of the thickness of the specimen at one point which gives the value in mm (millimeter). Similarly measurement is taken at five different points of the specimen and then the average value is taken which is to be used for the calculations.

3.2.3 Bulk :-

Bulk of the paper or paperboard is inverse of the apparent density. Bulk is used to measure the ratio of paper thickness to its weight in cubic centimeters per gram. Bulk expresses the specific volume of a material[11]. Bulk can be calculated with the help of data of grammage and thickness of the specimen

$$bulk(cm^3/g) = \frac{thickness\ (mm)}{grammage\ (\frac{g}{m^2})} \times 1000$$

Hence from the equation[11] we can see that by increasing thickness at same grammage we can easily increase the bulk of the paperboard.

3.2.4 Tensile Strength :-

Maximum force sustained by the specimen per unit specimen width without rupture is termed as tensile strength of the specimen[12]. Tensile strength of the specimen can be calculated by following equation.

$$Tensile\ Strength\ (kN/m) = \frac{Load\ at\ break\ \ (kN)}{Initial\ sample\ width\ (m)}$$

Figure 14 : A tensile tester

For the test to be performed we cut 10 strips of 15mm width from 5 paperboards formed of the same material and composition. A test specimen of approximately 100mm length is clamped between the jaws of the tensile tester and then load is applied in the longitudinal direction at the elongation rate of 10mm per minute. When the strip get ruptured the movement of jaws stops and the data is recorded like tensile strength, tensile index, load at elongation, breaking length, tensile energy absorption.

Tensile Index is also an important property which is used to make comparison between strengths of the specimens. It is given by the following equation[12].

$$tensile\ index\ \left(\frac{Nm}{g}\right) = \frac{tensile\ strength\ (\frac{N}{m})}{grammage\ (\frac{g}{m^2})}$$

3.2.5 Bending Stiffness :-

To the converter or end user, bending stiffness is a critical parameter for both paper and paperboard which impacts heavily on conversion and packaging line efficiency. Maximum stiffness has to be achieved at the lowest possible grammage and thereby cost, whilst maintaining a consistent and uniform level. Beyond the packaging line, stiffness continues to play an important role in the distribution chain right through to the retailer and then the consumer. Stiffness is defined as the paperboard's resistance to bending caused by a given applied force.

Stiffness can also be defined as a measure of the force which must be applied to deflect a defined piece of material through a defined distance or angle. This definition is applied to the most generally accepted methods of stiffness measurement. High values of stiffness can be achieved with high thickness and a high modulus of elasticity concentrated in the outer layers of a multi-ply sheet.

This approach to increasing stiffness can be compared to the I-beam principle, which offers a higher rigidity per unit weight when compared with a solid cross section.

Figure 15 : bending stiffness tester

For a homogeneous beam of thickness t and rectangular cross section the following well known equation[7] for the bending stiffness per unit width is given as

$$bending\ stiffness = \frac{E\ \times thickness^3}{12}$$

Where E, the constant of proportionality, is called the elastic modulus or Young's modulus,expressed in N/m^2 or Pa. Two Samples of rectangular dimension of 50mm × 38mm from each multilayered handsheet formed is cut[13] . Similarly we cut a total of 10 samples from 5 multilayered handsheets that we have formed of the same composition. Now each test specimen was placed between the jaws of the L & W stiffness tester and bending length was set to 50mm and bending angle was set to 5°.

Two readings for each sample is recorded and then average of all the values obtained is to be considered as the bending stiffness of the multilayered paperboard of specific composition.

3.2.6 Internal Bond Strength Or Scott Bond Test :-

The scott bond or internal bond strength tester measure the delamination resistance offered by paper or paperboard[14]. The internal bond strength is the bond energy between two layers of multilayered paperboard. It shows that how well is fiber to fiber bonding between two different layers of the multiply paperboard.

Figure 16 : Internal bond strength tester

Test specimen of 30×30 mm is cut from each sheet from 5 different sheets of similar composition. Now each test specimen is pasted to rectangular metal jaws on both the sides and then given a pressure of 20 psi for approximately 30 seconds by compression forces. After that the test specimen along with the metal jaws is clamped to the cylindrical metal pins and then given a delamination force in the z direction. The two metal jaws gets separated from each other giving us the values of the internal bond strength. Five values from hand sheets of the same compositions are recorded and then the average value is taken for comparing the internal bond strength of the sample with samples of other compositions.

3.3 SHOPPER RIEGLER FREENESS TEST:-

SHOPPER RIEGLER TEST OR °SR TEST provides us information about the rate at which dilute suspension of the pulp may be dewatered.

3.3.1 Test method :-

We take 2g of pulp in 1000ml of water. Before proceeding further it must be checked whether the suspension is at 20°C temperature[15]. Then the suspension is poured into the fill chamber which has conical nipple inside it. The conical nipple is then lifted and then the suspension discharges. The fibers are retained on the screen and the filterate discharges. Composition of the fiber suspensions determines the drainage time of the fiber suspension. The filterate flows through the lateral outlet into the measuring beaker where the freeness is shown in °SR.

Figure 17 : A Shopper Riegler freeness tester

The retained fibers on the screen are then collected and dried to measure the actual weight of the fibers and then corrections are applied to the values from correction table.

3.4 DESIGN OF EXPERIMENT:-

For the multilayered board production the usual grammage of paperboard varies from 250 g/m^2 to 550 g/m^2, but in some special cases it can even rise upto 800 g/m^2 or more. Together with industrial partner "weig" it was decided that 300 g/m^2 is good grammage for laboratory trials.

The best multilayered structure would have been with 5 layers (2 outer layers and 3 middle layers of grammage 40-45 g/m^2 each), but the efforts in producing such a complex structure in the laboratory would have been too high, so we chose to have a 3 layered structure by combining three middle layer into one and having two outer layers.

Here is the table which describe trials performed:-

Table 1 : Design of experiments

Sr No.	Trial Performed	Material Used	Objective
1.	Shopper riegler freeness test	Wet Pulped Reference Weig, Dry Pulped Weig, Wet Pulped Reference Postendorf, Dry Pulped Postendorf	To compare the drainage properties of dry versus wet pulped fibers.
2.	Producing Single layer handsheet of 80 g/m^2 of both dry and wet pulped material from Weig	Wet Pulped Reference Weig, Dry Pulped Weig,	To check the effect of dry fibers on handsheet made of completely dry fibers versus handsheet made of completely reference wet pulped fibers. Thickness, bulk, stiffness, tensile index, breaking length were compared.
3.	Producing three layered paper board of 300 g/m^2 (80/140/80) with 0%,50% and 100% dry fibers in the the middle layer.	Wet Pulped Reference Weig, Dry Pulped Weig,	To examine the effect of adding dry fibers in the middle layer of the 3 layered paperboard and comparing its properties with 3 layered paperboard made of completely wet reference pulped fibers.
4.	Producing three layered paper board of 300 g/m^2 (80/140/80) with different types of dry fibers in the middle layer and wet pulped material from Porstendorf.	Wet Pulped Reference Porstendorf, I-55 Hz (Weig), TMP-55 Hz, TZ XI	To examine the effects of using different kinds of dry fibers in middle layer and then comparing resulting paperboard properties with paperboard made from completely wet pulped fibres.
5.	Producing three layered paper boards of 300 g/m^2 (80/140/80) with increasing amount of dry fibers in the middle layer (0%, 12.5%,25%,50%,75%)	Wet Pulped Reference Weig, I-55 Hz (Weig) Dry Fibers	To examine the variation in strength properties of the three layered paperboard with increasing amount of dry fibers in the middle layer and comparing it with three layered paperboard made of completely wet pulped reference.

6.	Producing three layered paperboards of 300 g/m^2 with same amount of overall dry fiber content i.e 23.33% in middle layer but with different structures i.e (80/140/80), (115/70/115) and (40/220/40)	Wet Pulped Reference Weig, I-55 Hz (Weig) Dry Fibers	To examine the effect of change in paperboard structure with same amount of overall dry fiber content in physical and strength properties of the 3 layered paperboards.
7.	Producing three layered paperboard of 300 g/m^2 with 12.5% dry fiber content in the middle layer but with additional disintegration of dry fibers for 2.5 min, 5 min, 7.5 min and 10 min of dry fibers at 3000 rpm in disintegrator.	Wet Pulped Reference Postendorf, I-55 Hz (Weig), TMP-55 Hz, TZ XI	To examine the effect of additional disintegration of dry fibers which are to be used in the middle layer of the 3 layered paperboard in physical and strength properties of the 3 layered paperboard.

CHAPTER 4 | RESULTS AND DISCUSSIONS

Firstly experiment was performed to determine drainage properties of dry defibrated fibers and conventional wet pulped reference. The test method we used for this purpose is Shopper Riegler freeness tester.

4.1 SHOPPER RIEGLER FREENESS TEST:-

Table 2 : Materials and their amount taken for the °SR test.

Sr No.	Material Used	Amount of material taken
1	Wet Pulped Reference Weig	2g
2	Dry Pulped Weig	2g
3	Wet Pulped Reference Postendorf	2g
4	Dry Pulp Postendorf	2g

SHOPPER RIEGLER TEST OR °SR TEST provides us information about the rate at which dilute suspension of the pulp may be dewatered.

4.1.1 Result :-

Table 3 : °SR Value obtained for different dry and wet pulped fibers.

Sr No.	Material Used	°SR value
1	Wet Pulped Reference Weig	38.50
2	Dry Pulped Weig	11.00
3	Wet Pulped Reference Postendorf	37.00
4	Dry Pulped Postendorf	11.50

Therefore from the results obtained, it is clear that the dewatering resistance of the wet reference pulp is almost more than thrice of the dewatering resistance of that of the dry pulp. Hence dewatering occurs fast when dry defibrated fibers are used as compared to wet reference pulp. The dewatering resistance is also known as freeness and it also indicates the degree of beating. More dewatering resistance means more beating and hence more mean fibril area which further contributes to more strength properties of the pulp. Hence it can be predicted from the above data that wet pulp will have more strength properties than dry pulp.

4.2 FIBER ANALYSIS:-

We analyzed fibers in the L & W fiber tester and got the following results :-

Table 4 : Fiber analysis of some dry and wet pulped fibers.

Type	Average Fiber Length (mm)	Average Fiber Width (µm)	Mean fibril area %
Wet Pulped Reference Weig	1.058	26.1	10.4
Wet Pulped Reference Porstendorf	1.105	25.9	7.8
Dry Pulped Weig, I-55 Hz	0.955	26.7	3.7

Here we can see from the above data that fibrillation of fibers during dry pulping is very less therefore producing stiff fibers with less relative bond area and also wet pulped fibers have more mean fibril area than dry pulped fibers due to disintegration operation applied on wet fibers in the disintegrator for pulping. Due to disintegration with water more fibrils separate from the fibers of wet pulped reference fibers which contributes to the more bonding between fibers and hence more strength properties, as also predicted by °SR test.

Now we plotted graphs of some properties of the hand sheets obtained to check the effect of dry defibrated fibres. Here the properties we compared of the dry pulped Weig and wet reference Weig are represented by following graphs.

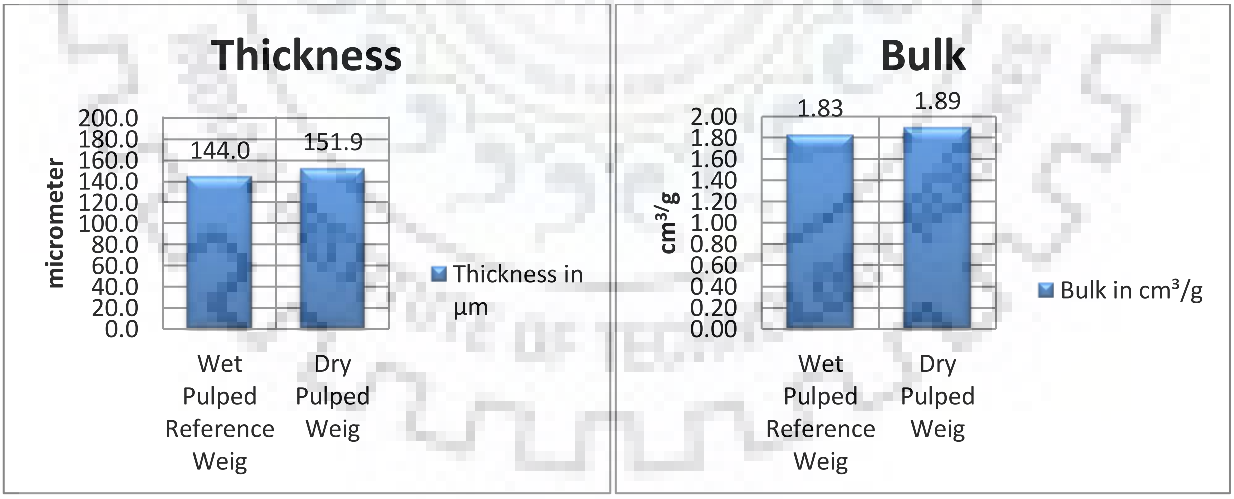


Figure 18 : Thickness and Bulk Comparison of sheets made of wet pulp and dry pulp.

Now we can easily interpret from the graphs we plotted that for the handsheets of almost same grammage the thickness obtained for the handsheet of dry pulped Weig is more than the thickness obtained for the handsheet of wet pulped reference Weig.

Also we can see due to increase in thickness for almost same grammage , bulk obtained for the handsheet of dry pulped Weig is more than that of wet pulped reference Weig.

Therefore this experiment clearly indicates that use of dry fibres results in higher sheet thickness and then consequently higher bulk because of more kinks and curls in dry fibers structure that causes fibers to make very less fiber to fiber bonds and occupy more volume.

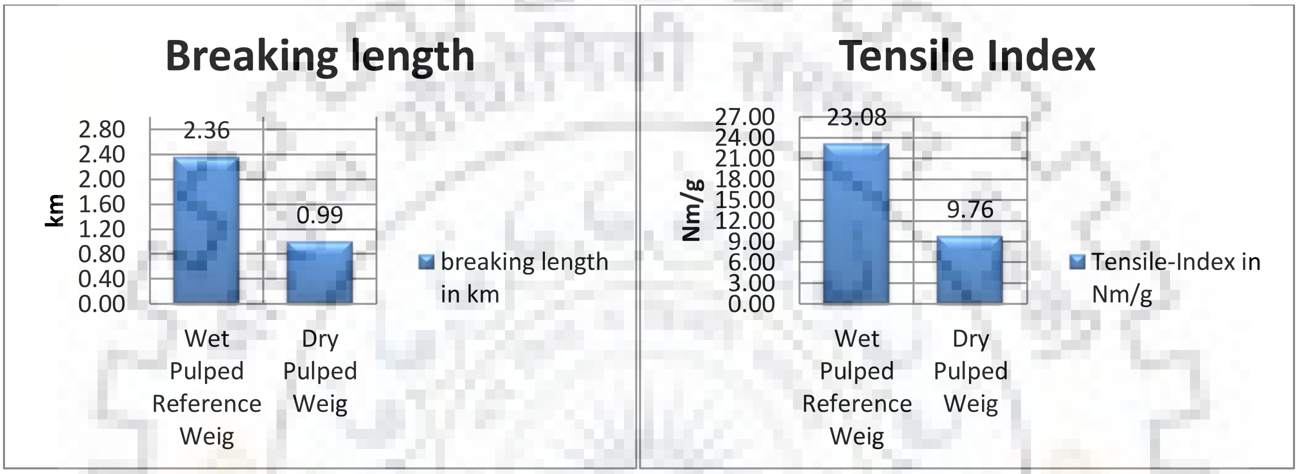


Figure 19 : Breaking length and Tensile Index Comparisons of sheets made of wet pulp and dry pulp.

On the other hand we also observed that though thickness and bulk of the dry pulped handsheet increased but other properties like tensile index, breaking length of the dry pulped handsheet reduced because of less fiber to fiber bond between fibers as we also know from the fiber properties that mean fibril area of dry fibers is less as compared to wet reference fibers which is responsible to make bonds between fibers. So it is interpreted from the results that dry pulped fibers must be used in combination with wet pulped reference in order to get the desired multilayered paperboard, which then can be used for packaging purposes. So We Practically made such multilayered paperboard which had middle layer of either completely dry fibres or combination of dry fibers with wet pulped fibers in order to get desired multilayered paperboard with enhanced properties for packaging purposes.

4.3 MULTILAYERED HANDSHEETS PREPERATION:-

Now after production of single layer handsheets of dry pulped weig and wet pulped reference weig, 3 layered handsheets were produced with top and bottom layer of wet pulped reference weig and middle layer of dry pulped weig. This was done to increase thickness and bulk of the middle layer of the paperboard with use of dry fibers in middle layer while keeping grammage constant of all the layers with respect to paperboard of all 3 layers of wet pulped reference weig.

So the grammage of the top layer was 80 g/m^2, and that of middle layer was 140 g/m^2 , and again of the bottom layer was 80g/m^2 . This was also done to create I-Beam effect which gives higher rigidity per unit weight when compared with a solid cross section. The top and the bottom layers of completely wet pulped reference weig gives high modulus of elasticity concentrated in the outer layers of the multiply sheet, which further will help in increasing bending stiffness of the paperboard.

(a) (b)

Figure 20 : Reference 3 layered paperboard structure a.) Wet Pulped, b.) Dry Pulped.

4.4 EFFECT OF INCREASING DRY FIBER CONTENT :-

In the following trial, 3 types of paperboard were formed as follows:-

i. Three layered paperboard of all the layers of wet pulped weig. (0% overall)
ii. Three layered paperboard with middle layer consisting 50% dry weig fibers. (23.33% overall)
iii. Three layered paperboard with middle layer of completely or 100% dry weig fibers.(46.67% overall)

After preparation of the paperboards, following graphs were plotted after testing their properties:-

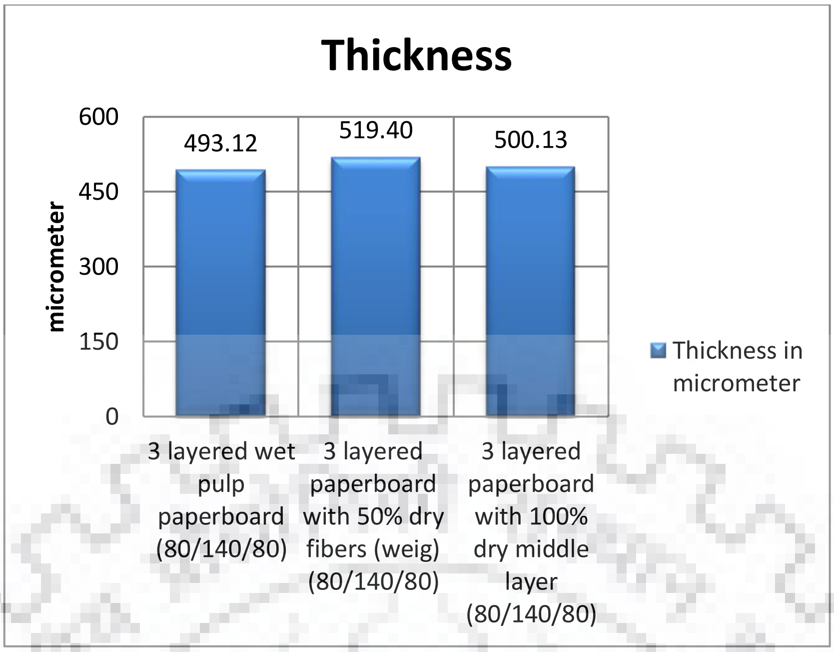


Figure 21 : Thickness variation upon adding dry fibers in middle layer.

We can clearly see that by adding dry fibers in the middle layer of 3 layered paperboard the thickness of the paperboard increases as compared to paperboard of completely wet pulped reference weig.

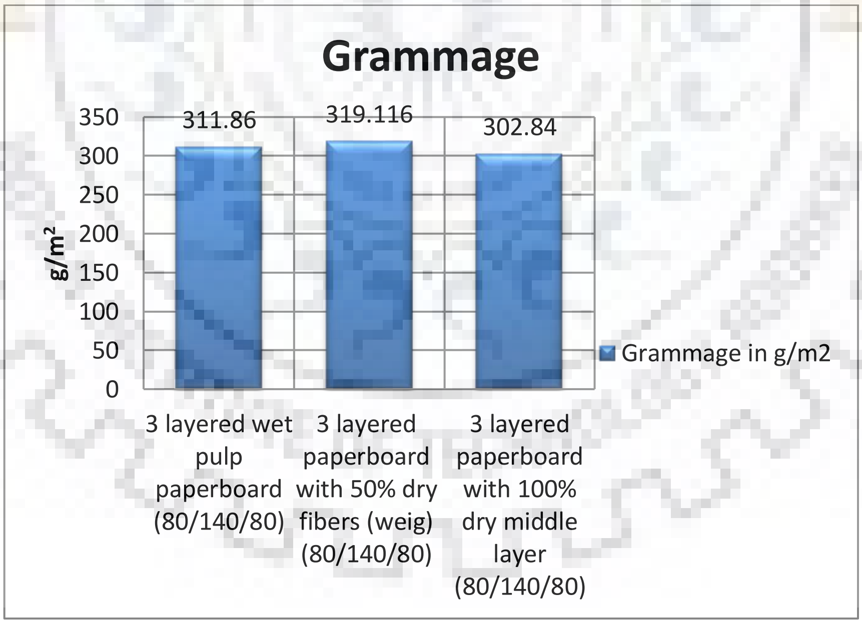


Figure 22 : Grammage variation upon adding dry fibers in middle layer.

The thickness of the paperboard with 100% dry fibers should be greater than that of one with 50% dry fibers but due to more grammage of the paperboard with 50% dry fibers, resulting thickness is slightly greater than that of paperboard with100% dry fibers in the middle layer.

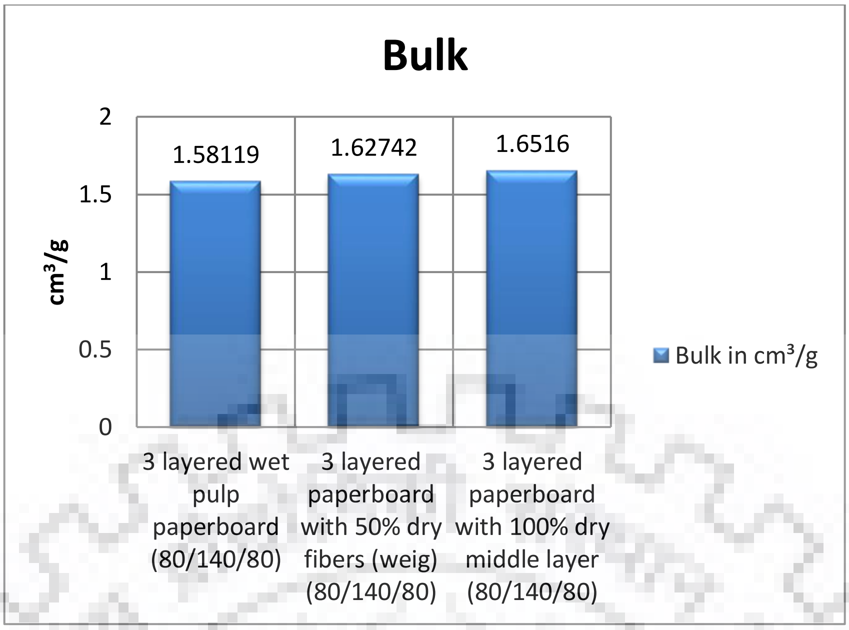


Figure 23 : Bulk variation upon adding dry fibers in middle layer.

Therefore from the graph we can clearly see that the bulk of the paperboard increases with increase in dry fibers content in the middle layer. The % increase in bulk for 50% dry fibers in the middle layer was 2.92% and for that of 100% dry fibers in the middle layer was 4.45%.

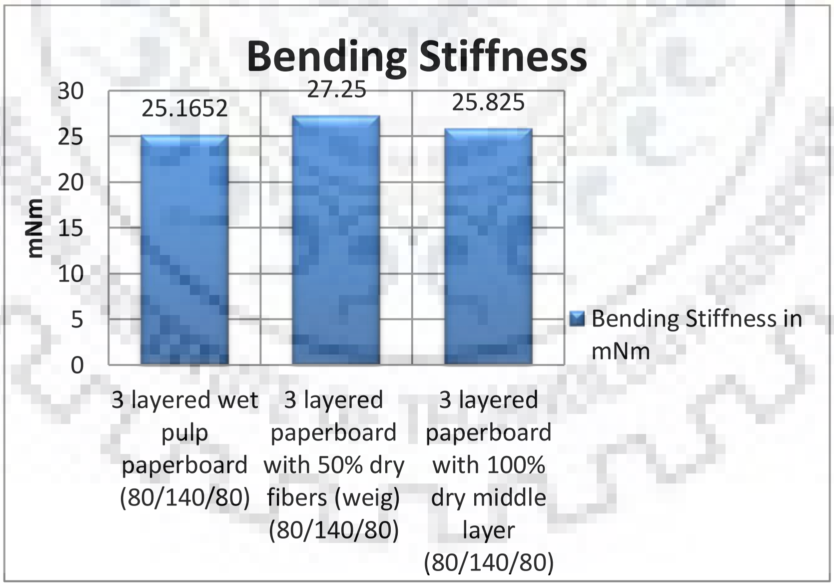


Figure 24 : Bending Stiffness variation upon adding dry fibers in middle layer.

The % increase in the bending stiffness by addition of dry fibers was 8.28% for the paperboard with 50% dry fibers in the middle layer and 2.62% for the 100% dry fibers in the middle layer of the three layer paperboard. The reason why the optimum of bending stiffness was achieved for 50 % dry fiber content in the middle layer and a further improvement by increasing up to 100 % was not possible anymore, is located in the lower strength potential of the dry fiber material. On one hand an increasing dry fiber content results in an increasing thickness/bulk, but on the other hand the structural strength decreases with increasing dry fiber content. Therefore we have to find the optimum balance so that the positive influence of the volume increase on the stiffness is not overcompensated by the decreasing structural strength.

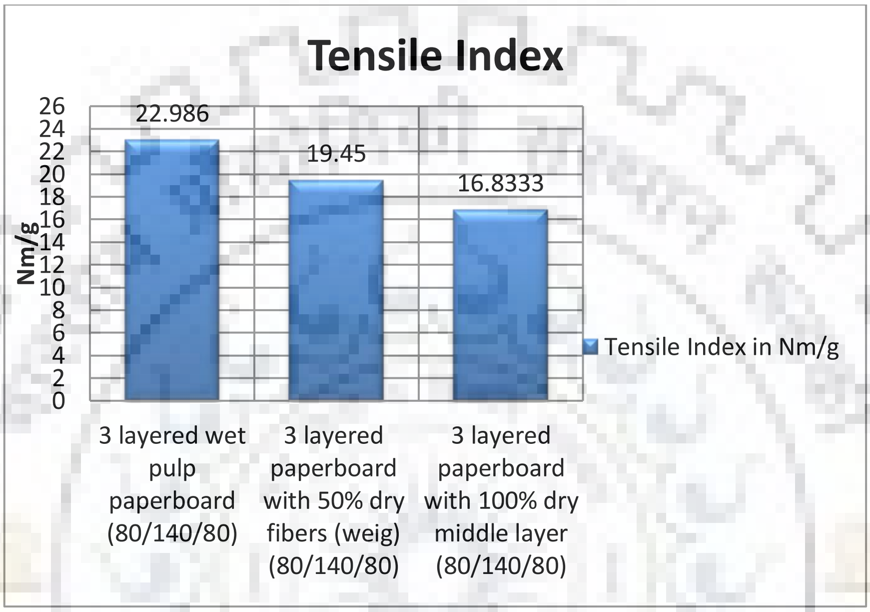


Figure 25 : Tensile Index variation upon adding dry fibers in middle layer.

Tensile Index of the paperboards decreases by adding dry fibers in the middle layer of the three layer paperboards. This happens due to poor fiber to fiber bonding and decrease in relative bonding area between dry fibers.

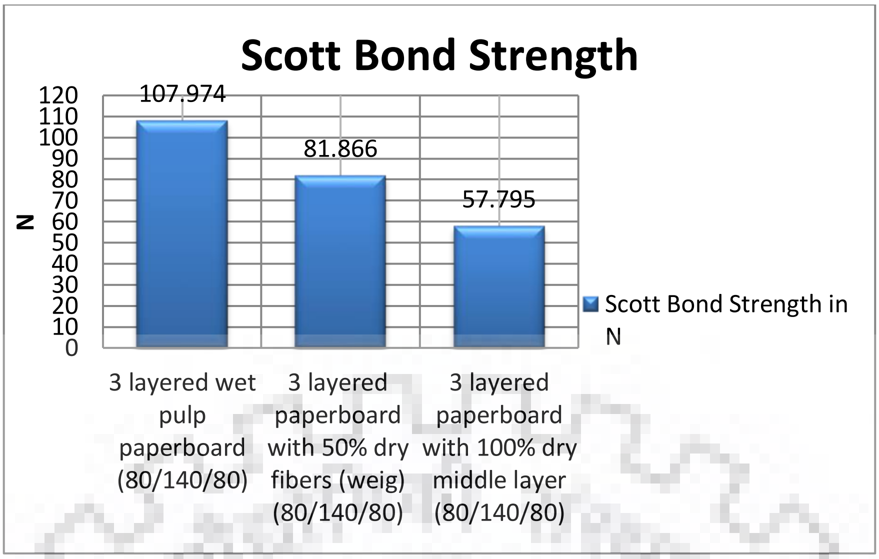


Figure 26 : Scott bond strength variation upon adding dry fibers in middle layer.

The Scott Bond or Internal Bond Strength also decreases with increase in amount of dry fibers in the middle layer of the 3 layer paperboard. This also occurs due to relative less fiber to fiber bonding between dry fibers as compared to wet pulped fibers.

As we can see though there is increase in thickness, bulk and bending stiffness of the 3 layer paperboard the other mechanical properties are getting reduced such as tensile strength and scott bond strength. So, in order to get 3 layered paper board with good overall properties we have to optimize the amount of dry fibers in the middle layer of the 3 layered paperboard and also we can use different type of dry fibers which can give enhanced properties to the multilayered paperboard. We can also employ the disintegration operation to the dry fibers to increase relative bonding area between the dry fibers to increase fiber-fiber bonding between the dry pulped fibers but it will also decrease some stiffness of the dry fibers due to increase in fiber flexibility. Therefore time of disintegration should also be optimized so that loss in stiffness is very less. We can also use the different reference wet pulped fibers to achieve the 3 layered paperboard with increased bending stiffness but with more or less same strength properties.

The following methods were used to compensate the decreasing strength properties of the multilayered paperboard

i. Disintegrating dry fibers in the disintegrator
ii. Using different kinds of dry fibers in the middle layer
iii. Optimizing the amount of dry fibers in the middle layer.
iv. Use of different wet pulped reference materials.

4.5 EFFECT OF CHANGE IN WET PULPED REFERENCE MATERIAL WITH DIFFERENT TYPES OF DRY FIBERS:-

Now for the next trials performed we changed the reference wet pulp from weig to porstendorf and also used different kinds of dry fibers to see the variations in the properties of the 3 layered paperboards.

The materials used for the next trials are depicted below:-

Figure 27 : Reference material for wet pulping from Porstendorf

And for the middle layer we used three different kinds of dry fibers with 1 min disintegration depicted as follows:-

Figure 28 : a) dry fibers I-55 hz from Weig b) TMP-55 hz dry fibers

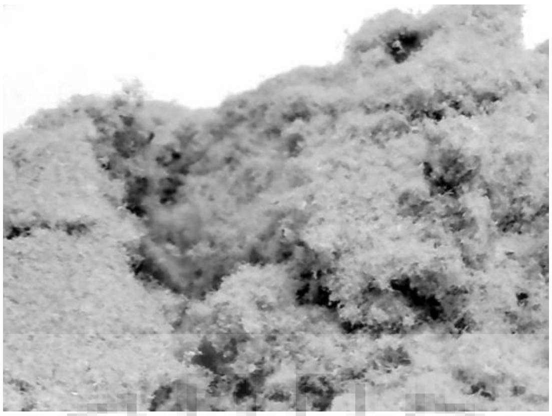


Figure 29 : TZ XI dry fibers

In this trial we performed we made 3 layered paperboard. The grammage of the top and the bottom layer of the paperboard was 80 g/m^2 and the grammage of the middle layer of the paperboard was 140 g/m^2 . Given below is the table of the types of 3 layered paperboard we prepared for the following trial.

Table 5 : Structure of the 3 layered paperboards with different kinds of dry fibers in the middle layer

Sr No.	**Types of fibers used (1 minute disintegration)**	**% of dry fibers in middle layer/ Overall dry fibers**	**Grammage**
1	I-55 Hz (Weig)	25% / 11.67%	300 (80/140/80)
2	I-55 Hz (Weig)	50% / 23.33%	300 (80/140/80)
3	TMP-55 Hz	25% / 11.67%	300 (80/140/80)
4	TMP-55 Hz	50% / 23.33%	300 (80/140/80)
5	TZ XI	25% / 11.67%	300 (80/140/80)
6	TZ XI	50% / 23.33%	300 (80/140/80)

The above mentioned paperboard were prepared and then then they were compared with the paperboard made of completely wet reference pulp material of postendorf of same grammage i.e 300 g/m^2 .

The Results we obtained are depicted graphically below:-

Firstly we plot the graphs of thickness of the three layered paperboards produced which are depicted as follows

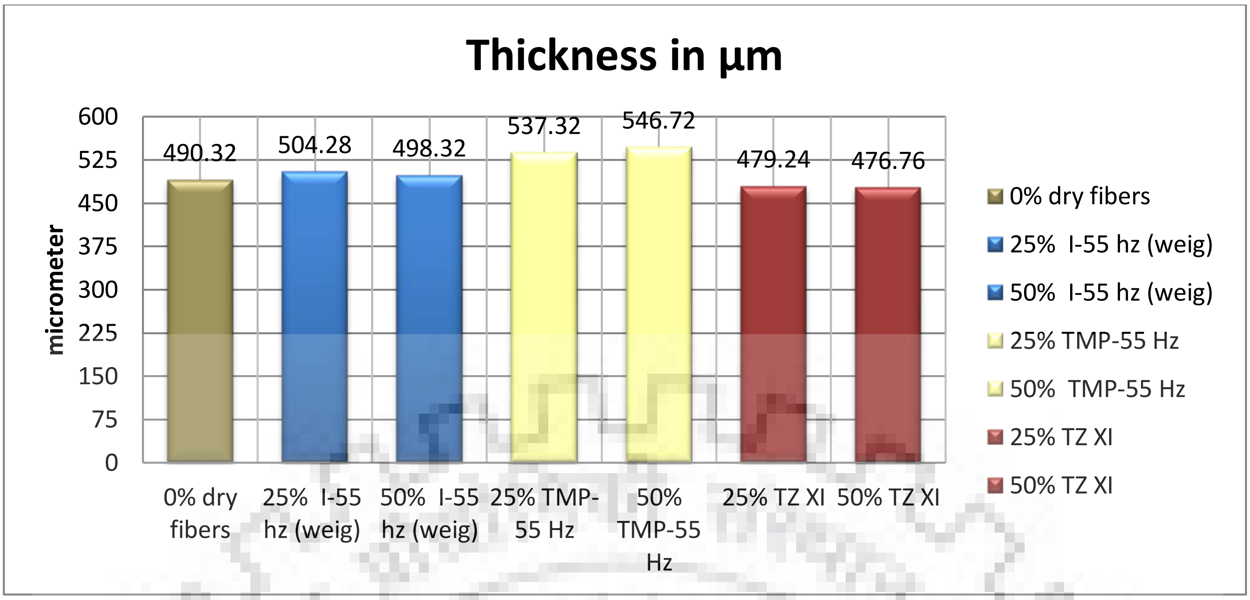


Figure 30 : Thickness variation using different types of dry fibers in the middle layer.

Here from the above plots we see that using TMP 55 Hz dry fiber in the middle layer gives highest thickness for the 3 layered paperboards at approximately same grammage of about 300 g/m^2 . This can be due to more stiffer, hard and rigid fibers of TMP-55 Hz with more kinks.

Now for the Bulk and Bending Stiffness following Graphs are plotted.

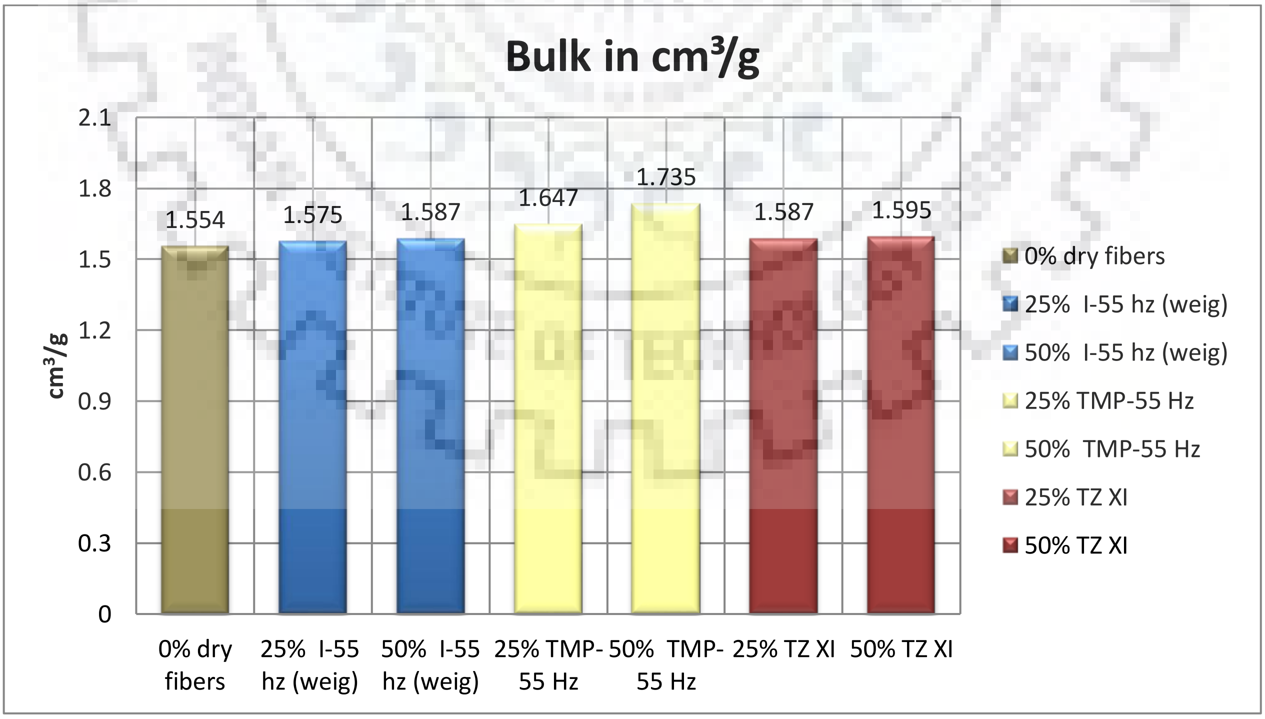


Figure 31 : Bulk variation using different types of dry fibers in the middle layer.

Table 6 : % increase in bulk for different kinds of dry fibers used.

TYPE	BULK (cm^3/g)	% increase in Bulk	% of overall DF used
PORSTENDORF	1.554	-	0
I-55 Hz (Weig) 25%	1.57495	1.34%	11.66%
I-55 Hz (Weig)50%	1.58706	2.13%	23.33%
TMP-55 Hz 25%	1.64732	6.005%	11.66%
TMP-55 Hz 50%	1.73482	11.63%	23.33%
TZ XI 25%	1.58748	2.15%	11.66%
TZ XI 50%	1.59491	2.63%	23.33%

Now from the data we can easily conclude that TMP-55 Hz dry fibers gives highest increase in bulk, and we can also conclude that using 50% dry fibers in middle layer always gives higher bulk than using 25% fibers in the middle layer of three layered paperboard. Hence it is demonstrated that using dry fibers will result in increase in bulk and more the amount of dry fibers are used more will be the increase in bulk.

Now for Bending Stiffness we obtained following plot.

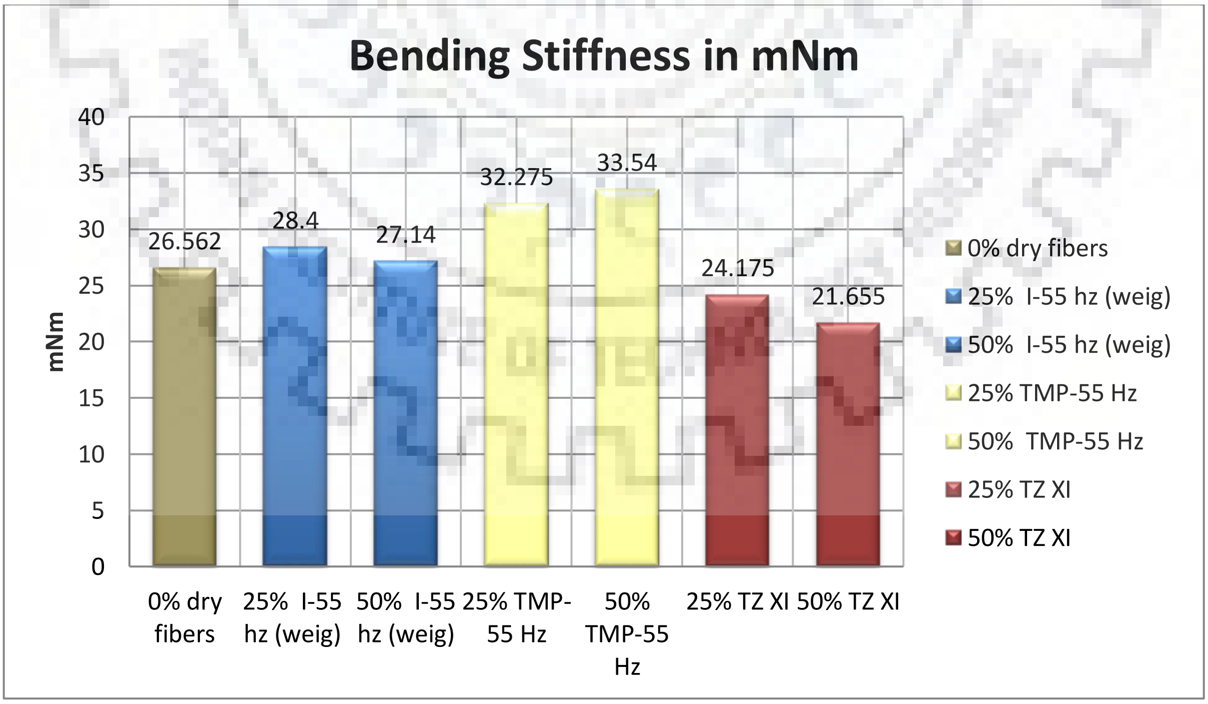


Figure 32 : Bending Stiffness variation using different types of dry fibers in the middle layer.

Here from the above plot of bending stiffness we see that bending stiffness of 3 layered paperboard increases by adding I-55 Hz and TMP-55 Hz dry fibers in comparison to paperboard made of completely wet pulped reference material of Postendorf but in case of addition of TZ XI dry fibers it decreases. The low grammage and therefore thickness of the paperboard handsheets produced from TZ XI fibers could also be the reason for low bending stiffness of the TZ XI paperboard due to strong relation of bending stiffness and thickness. TMP-55 hz paperboard with 50% fibers gives highest increase in bending stiffness of 25%.

Hence we see that adding dry fibers in the middle layer will always result in increase in bulk of the 3 layered paperboard having same grammage as the reference paperboard of completely wet pulped materials, but not necessarily in bending stiffness of the paperboards also.

Also we have to optimize the amount of dry fibers in the middle layer so that we get increase in both bulk as well as bending stiffness.

The plots for other strength properties like scott bond strength and tensile index are depicted below

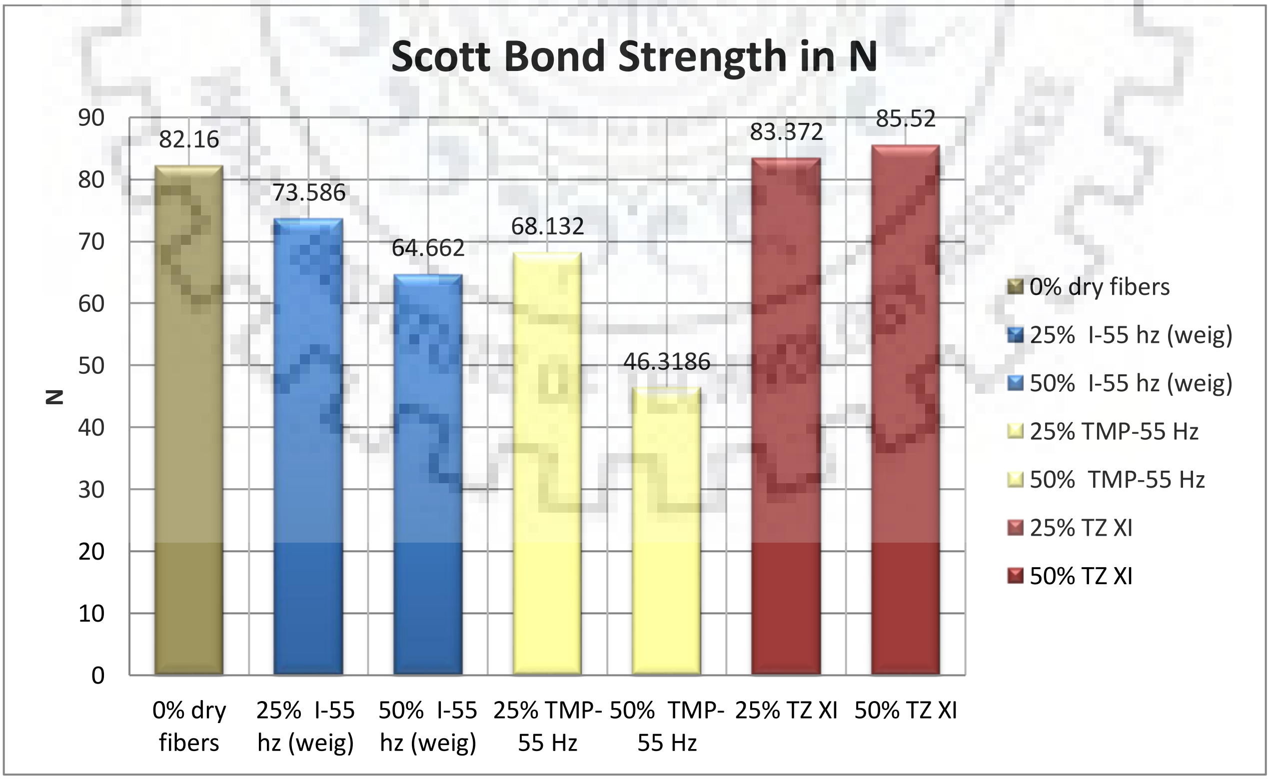


Figure 33 : Scott Bond Strength variation using different types of dry fibers in the middle layer.

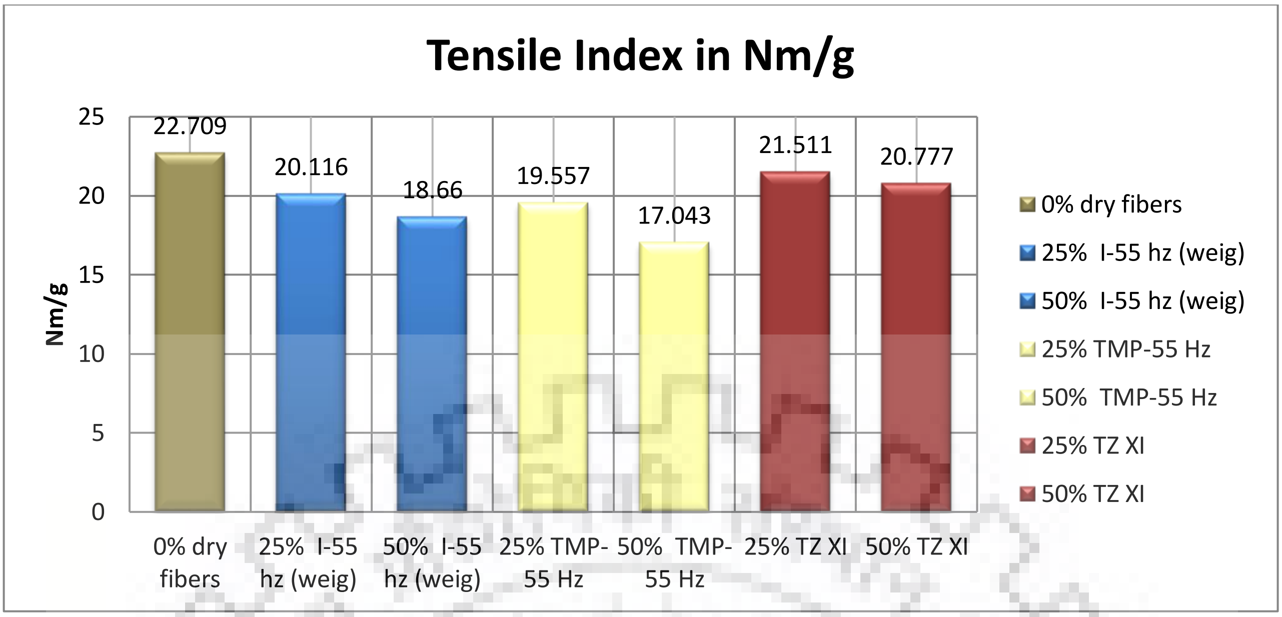


Figure 34 : Tensile Index variation using different types of dry fibers in the middle layer.

Here we see similarity in variations of internal bond strength and tensile index of 3 layered paperboards with all 3 different types of dry fibers. Both the properties decrease with increase in dry fiber content from 25% to 50% in the middle layer for all the three kinds of paperboards.

Though TZ XI show comparable tensile and internal bond strength to paperboard made of complete Postendorf, TMP-55 Hz show least of the both the properties as expected because of more stiff and rigid fibers of TMP-55 Hz with more kinks and therefore very less bonding area between its fibers.

Also one more important observation was noted that increasing the amount of dry fibers in the middle layer caused both the properties to decrease in all the 3 layered paperboards we prepared using all 3 kinds of dry fibers.

Hence from the above observations we get to the following results:-

i. Increasing amount of dry fibers in the middle layer will always result in increase in bulk of the 3 layered paperboard but not necessarily in the bending stiffness of the paperboard.
ii. Increasing amount of dry fibers resulted in decrease in strength properties like internal bond strength and tensile strength for I-55 Hz and TMP 55 Hz. But for TZ XI scott bond strength improved a little bit and tensile index decreased just a little bit.
iii. We have to optimize the amount of dry fibers in the middle layer so that we obtain increase in both bulk and bending stiffness of the paperboards with more or less same strength properties

with reference to the paperboard made of complete wet pulped reference material. For this we have to prepare paperboards with varying dry fiber contents in the middle layer of the paperboard and then see at which concentration of dry fibers in the middle layer we get increment in bending stiffness but decrease in tensile strength and internal bond strength is insignificant.

4.6 EFFECT OF INCREASE IN DRY FIBER CONTENT IN THE MIDDLE LAYER OF THE THREE LAYER PAPERBOARD:-

Now based on the above results we obtained, we decided to go with following materials for the next trial:-

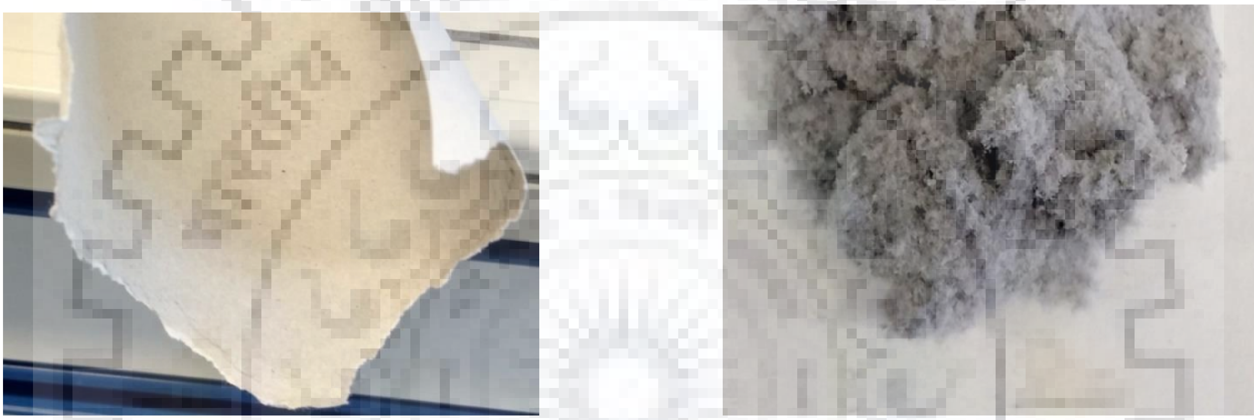


Figure 35 : a)Reference material from Weig b) Dry fibers I-55 Hz from Weig

Now in this trial we made 3 layered paperboards using reference material from Weig for wet pulping in disintegrator for the top and the bottom layer of the paperboard and I-55 Hz dry fibers to be used in middle layer along with combination from reference material for wet pulping. The types of paperboards we prepared for this trial are listed below.

Table 7 : 3 layered paperboard produced with increasing amount of dry fibers content in the middle layer.

Type	Grammage	% dry fibers in middle layer	Overall % dry fibers
Weig	300 (80/140/80)	0	0
Weig and I-55 Hz	300 (80/140/80)	12.5	5.83
Weig and I-55 Hz	300 (80/140/80)	25	11.67
Weig and I-55 Hz	300 (80/140/80)	50	23.33
Weig and I-55 Hz	300 (80/140/80)	75	35

After testing the properties of the paperboard made we obtained the following results depicted by the following graphs:-

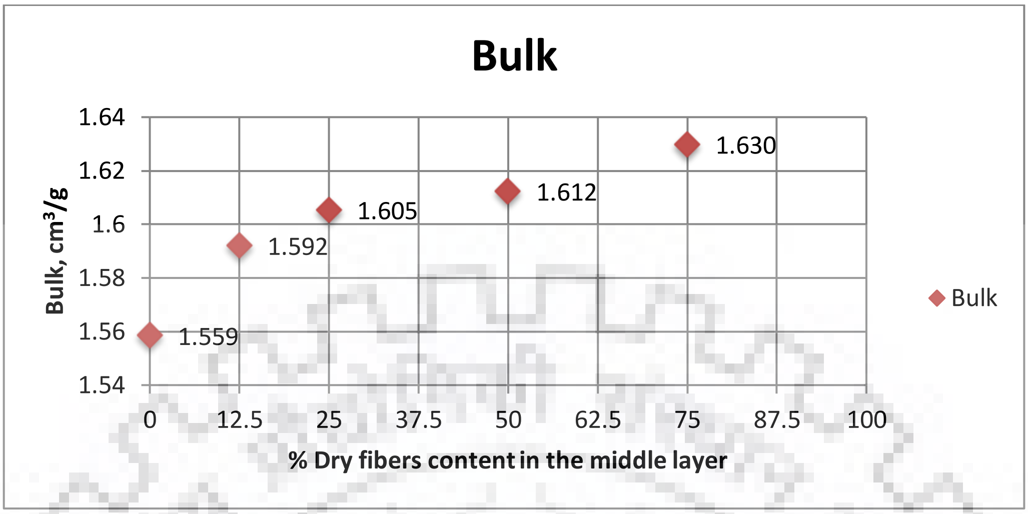


Figure 36 : Bulk vs % Dry fibers content in middle layer, (80/140/80)

Now we can see from the above drawn plot that with increase in the dry fiber content in the middle layer, the bulk of the three layer paperboard increases hence it proves the potential of the dry fibers to increase bulk while keeping the grammage of the paperboard almost constant due to the more rigid nature of dry fibers with more kinks and curls that provides very less relative bond area for dry fibers to make bonds and thus occupy more space than conventional wet pulped fibers.

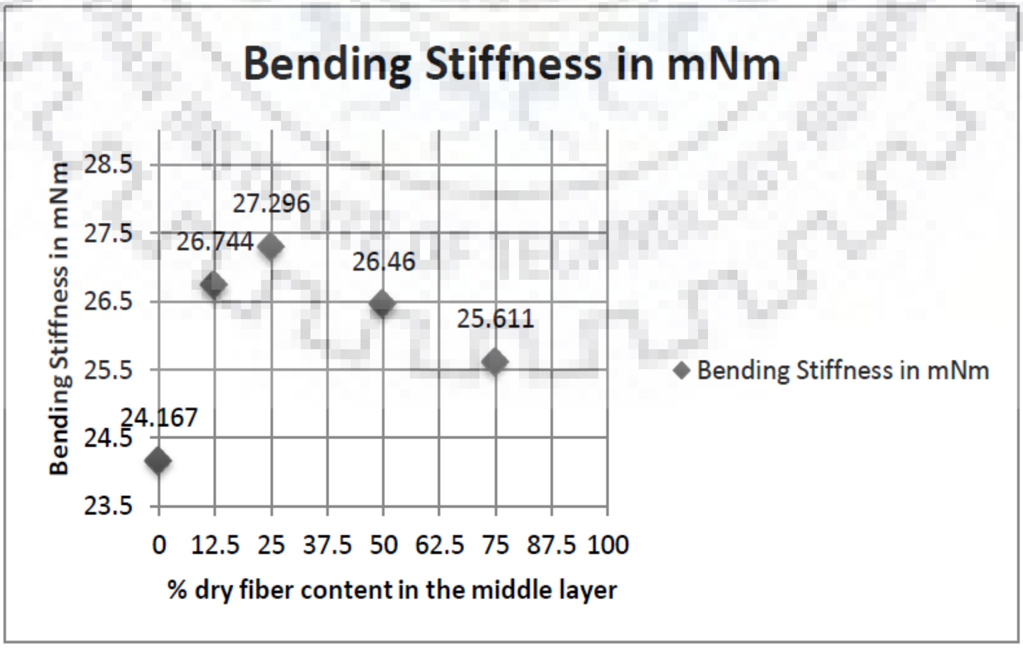


Figure 37 : Bending Stiffness vs % Dry fibers in middle layer, (80/140/80)

Here from the plot we can see that bending stiffness is increased in all the cases with adding dry fiber content in the middle layer as compared to paperboard made of whole wet pulped fibers, but we also see fluctuations due to high dependence of bending stiffness on thickness and modulus of elasticity. So it is clear from the plot that we have to optimize dry fiber content in the middle layer so that we can utilize maximum potential of the dry fibers positively.

Now for the internal bond strength (Scott type) we obtained the following plot:-

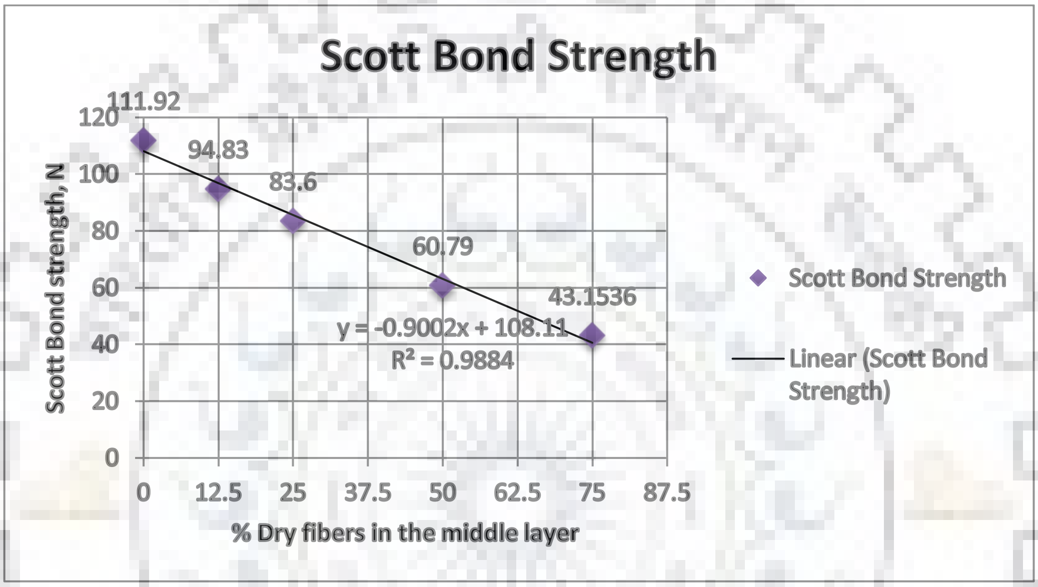


Figure 38 : Scott Bond strength vs % dry fibers in middle layer (80/140/80)

Here from the above graph we found that Scott bond strength decreases almost lineary with increase in dry fiber content in the middle layer with regression coefficient of 0.9884 which is logical because as we increase dry fibers content in the middle layer the bonding in the middle layer of the paperboard decreases due to less relative bonding area or less mean fibril area of the dry fibers due to which there is very poor bonding between the fibers which is also supported by fiber analysis data and hence when force is applied in two opposite sides of the z- plane, the paperboard de laminate easily from the middle layer as dry fiber content increases in the middle layer.

Now for the tensile index following plot were obtained:-

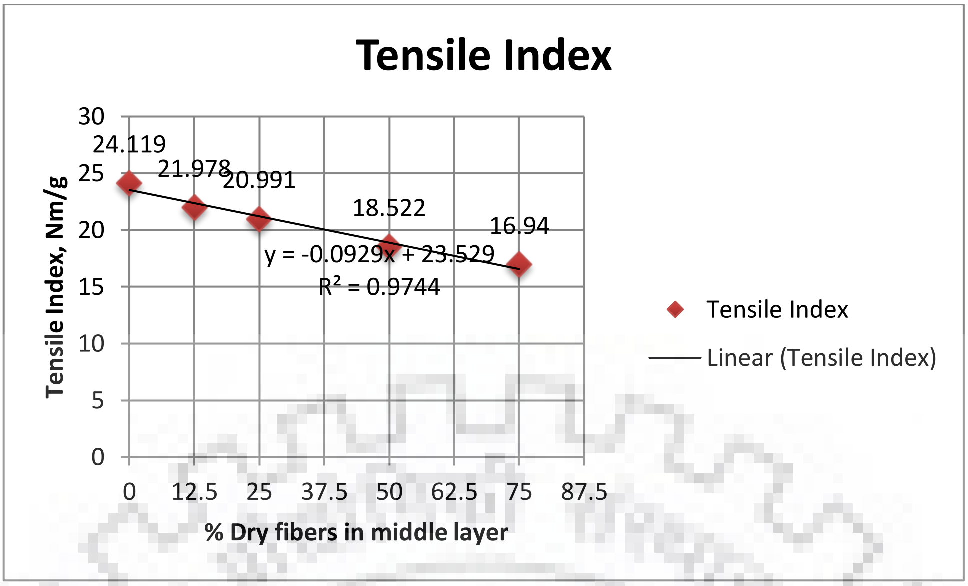


Figure 39 : Tensile index vs % Dry fibers in middle layer (80/140/80)

Here same is the case with tensile index as Scott Bond srrength it also decreases linearly with increase in dry fiber content in the middle layer with the regression coefficient of 0.9744 due to poor bonding in middle layer as dry fiber content increases because as we know that dry fibers have poor fiber-fiber bonding.

Here from the above plots it is clear that both internal bond strength and tensile index reduces by increasing amount of dry fibers in the middle layer due to less relative bonding areas of dry fibers. So we chose the paperboard with has 12.5% dry fibers in the middle layer because it gives improved bending stiffness for paperboards with little decrease in other strength properties like Scott Bond Strength and Tensile Index as compared with reference paperboard of complete wet pulped reference material

Table 8 : % increase in bending stiffness by increasing dry fiber content in the middle layer of the 3 layered paperboard.

Type	**Bending Stiffness in mNm**	**% Overall Dry Fibers**	**% increase in Bending Stiffness**
Weig(80/140/80)	24.167	0	-
Weig, I-55 Hz 12.5% (80/140/80)	26.744	5.83	10.66
Weig, I-55 Hz 25% (80/140/80)	27.296	11.67	12.95
Weig, I-55 Hz 50% (80/140/80)	26.46	23.33	9.48
Weig, I-55 Hz 75% (80/140/80)	28.611	35	18.38

Table 9 : % increase in bulk by increasing dry fiber content in the middle layer of the 3 layered paperboard.

Type	Bulk in cm^3/g	% Overall Dry Fibers	% increase in Bulk.
Weig(80/140/80)	1.558	0	-
Weig, I-55 Hz 12.5% (80/140/80)	1.592	5.83	2.18
Weig, I-55 Hz 25% (80/140/80)	1.605	11.67	3.02
Weig, I-55 Hz 50% (80/140/80)	1.612	23.33	3.46
Weig, I-55 Hz 75% (80/140/80)	1.629	35	4.56

Therefore from the above table we see that using 12.5% dry fibers in the middle layer gives about 10.66% increase of bending stiffness and 2.18% increase in bulk of the three layered paperboard as compared to reference paperboard of completely wet pulped material with less decrease in other strength properties like tensile strength and internal bond Strength.

4.7 EFFECT OF CHANGE IN STRUCTURE WHILE KEEPING THE OVERALL AMOUNT OF DRY FIBERS CONSTANT IN 3 LAYERED PAPERBOARD:-

Now in this trial we also added two new types of paperboard structure with overall dry fiber contents of 23.33% along with one trial from previous section with 23.33% overall dry fiber content and (80/140/80) structure. The new trials added are explained below :-

i. One is with more thicker outer layers of grammage 115 g/m^2 and middle layer of grammage 70 g/m^2 with 100% dry fibers in middle layer
ii. One is with more thicker middle layer of grammage 220 g/m^2 with 31.81% dry fibers in the middle layer and very thin outer layers of grammage 40 g/m^2 .

This was done to see the effect of change in structure of the paperboard of outer layers and middle layers of the multiply 3 layered paperboards. Following results were obtained which are depicted graphically.

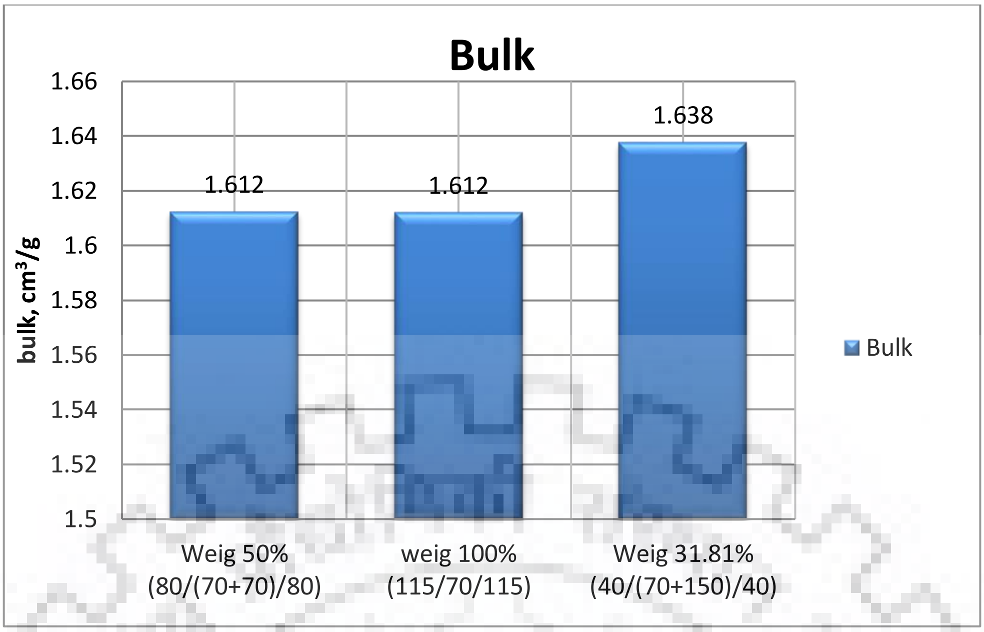


Figure 40 : Bulk variation with 23.33% overall dry fibers in 3 different paperboards.

Here we can see from the plot that the highest bulk is obtained for the paperboard which have most thicker middle layer of grammage 220 g/m^2 and 23.33 % dry fiber overall. This is because, in case of 220 g/m^2 of middle layer, the dry fibers have more volume to spread in the sheet thus resulting in more bulk of the paperboard whereas the bulk obtained for (80/140/80) and (115/70/115) are almost equal.

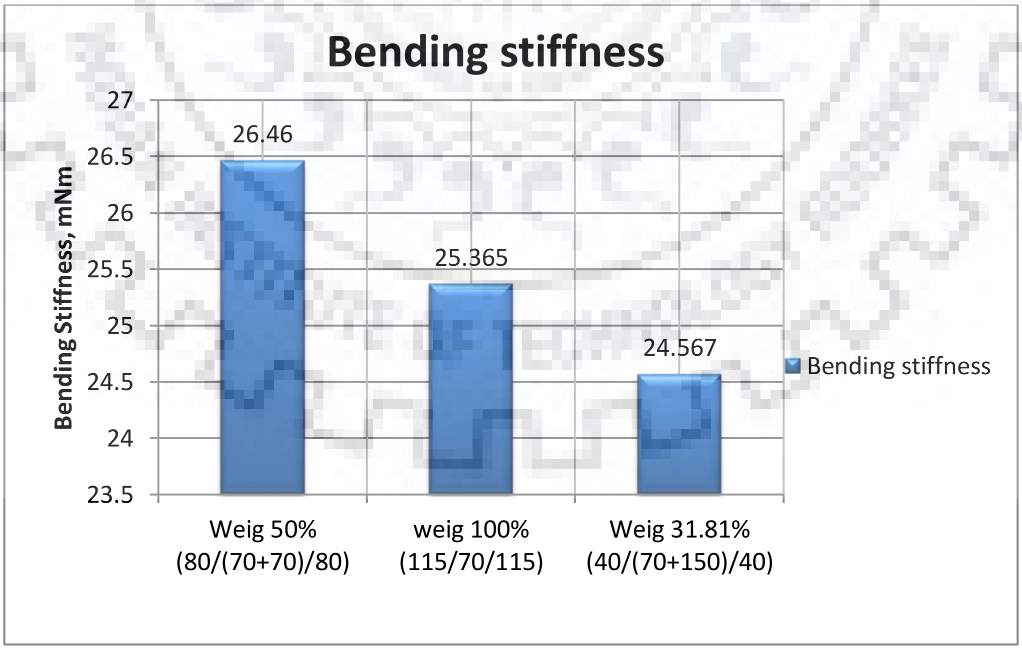


Figure 41 : Bending Stiffness variation with 23.33% overall dry fibers in 3 different paperboards.

Now here from the results it can be interpreted that 3 layered paperboard with structure (80/140/80) gives more bending stiffness as compared to paperboard with (115/70/115) and (40/220/40) while using same amount of dry fibers 23.33% of the overall grammage.

This is due to wet pulped reference material gives more strength to the paperboard when used in outer layers and dry fibers are rigid and stiff in the middle layer which contributes to the bending stiffness of the paperboard. Dry fibers also gives more thickness at same grammage so more thicker paperboard can be made using less material when used in middle layer. That is the reason middle layer is made thicker when producing 3 layered paperboards, but it should also be noticed that if top and bottom layers are made very thin, then also bending stiffness decreases as can be seen from the graph in case of paperboard with (40/220/40) structure because of depending of bending stiffness on modulus of elasticity of top and bottom layer as well. As we know that top and bottom layer have good strength properties than middle layer therefore decrease in thickness of top and bottom layer results in decrease of bending stiffness of the overall paperboard.

Now for internal bond strength (Scott type) following plot was obtained:-

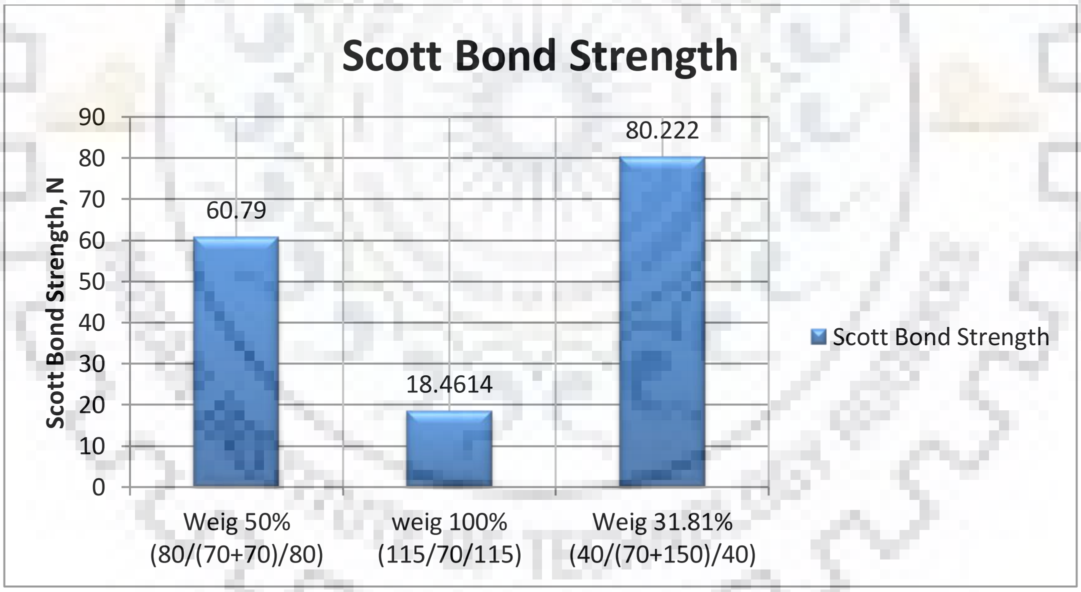


Figure 42 : Scott Bond Strength variation with 23.33% overall dry fibers in 3 different paperboards.

Here from the above plot we can see that Scott Bond Strength of the paperboard with (115/70/115) structure has drastically lower value. There could be two reasons for that, firstly we can see from the structure the grammage of the middle layer is very small i.e only 70 g/m^2 and secondly the middle layer is not been mixed with conventional wet pulped fibers and has 100% dry fibers content in the middle layer due to which there is very poor bonding in the middle layer and then, when the force is applied in the opposite directions of the plane middle layer collapses very easily.

Now for the variation of tensile Index following plot was obtained:-

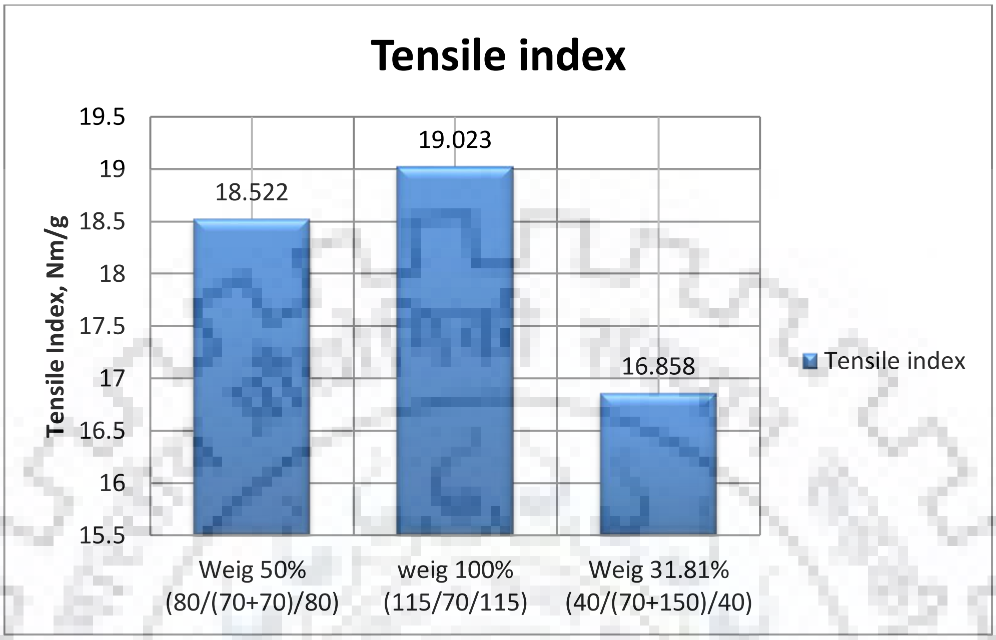


Figure 43 : Tensile Index variation with 23.33% overall dry fibers in 3 different paperboards.

Here from the above plot we see that 3 layered paperboard with (115/70/115) structure as highest tensile index among the three because of thicker outer layers of conventional wet pulped fibers which have good fiber to fiber bonding ability than dry fibers which is also supported by the fiber analysis and freeness test of the fibers done earlier in this work and that is also the reason of lowest tensile index of paperboard with structure (40/(70+150)/40) because of thinnest outer layers.

4.8 EFFECT OF DISINTEGRATION OF DRY FIBERS :-

Now we have seen that using dry fibers in the middle layer results in increase in Bending Stiffness and decrease in other strength properties. However, if the dry fibers are additionally wet disintegrated, the volume or bulk will be reduced and the strength will increase due to the improved fiber flexibility and a re-fibrillation on the fibre surface (a quasi-reactivation of the fiber-strength potential), but it should be kept in mind that the bending stiffness is to be regarded as a special case, because it is influenced by the modulus of elasticity as well as thickness of the paperboard and these two influencing factors are sometimes diametrically opposed to each other. Now in order to increase strength properties of the dry fibers we decided to disintegrate the dry fibers in the disintegrator to increase the mean fibril area of the dry fibers and also to bring the fibers more close by increasing fiber flexibility to make more fiber-fiber bonds. Disintegrator was used for this operation which was operating at 3000rpm. We prepared different paperboards with following disintegration times:-

i. 2.5 min, 3000rpm
ii. 5 min, 3000rpm
iii. 7.5 min, 3000rpm
iv. 10 min, 3000rpm

The 3 layered paperboard was made of grammage 300 g/m^2 with both top and bottom layer being 80 g/m^2 and the middle layer being 140 g/m^2 containing 12.5% dry fibers. The wet pulped reference material was from Weig and the dry fibers we used were I-55 Hz from Weig.

Figure 44 : 3 layered paperboard with wet pulped reference weig and I-55 Hz weig dry fibers (12.5%), 2.5 min disintegration

Following plots were obtained depicting effect of disintegration:-

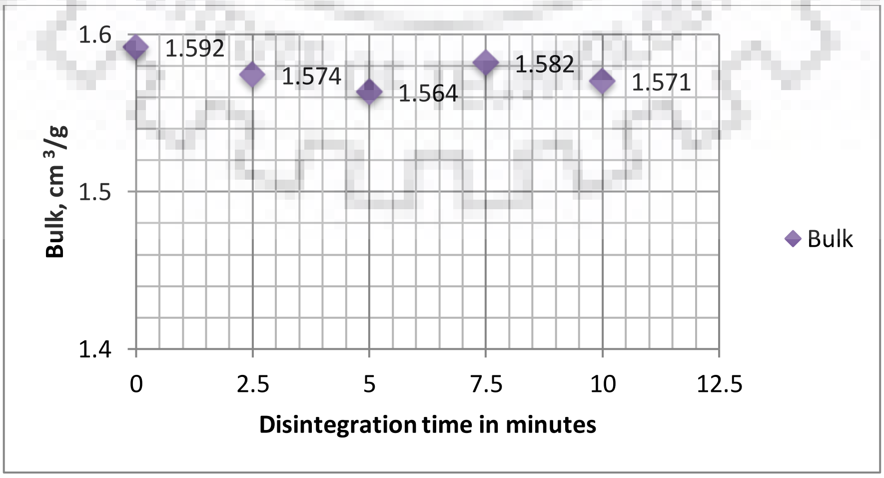


Figure 45 : Bulk vs Disintegration Time

As we can see from the graphs above with increase in disintegration time the bulk of the 3 layered paperboard showed decrease as compared to paperboard with no disintegration of dry fibers. This can be explained due to improved fiber flexibility so that fibers can come more closer to each other and occupy less space as compared to dry fibers without disintegration.

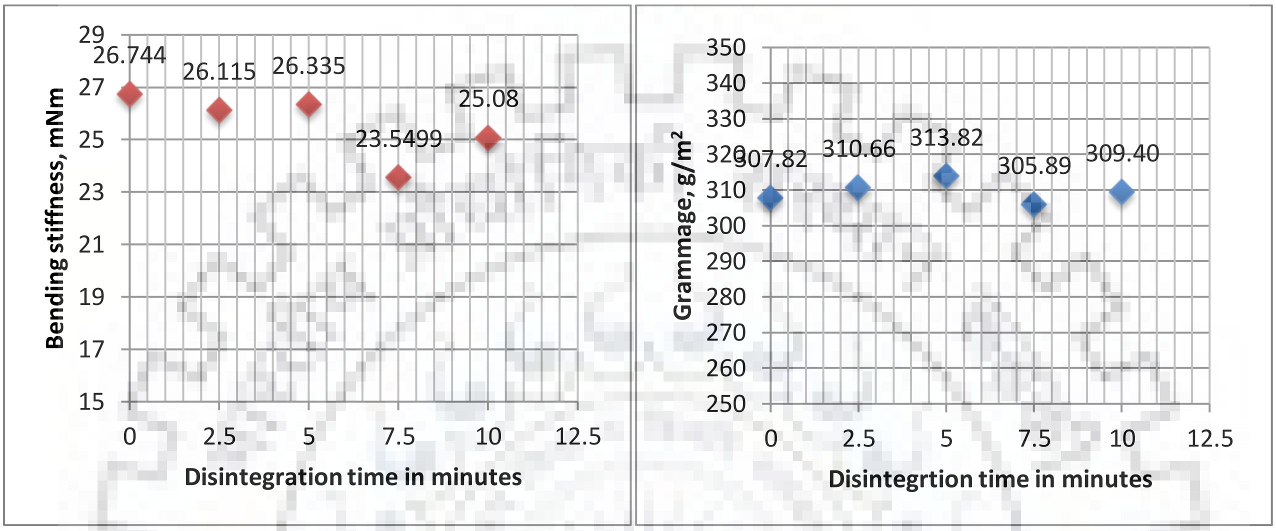


Figure 46 : a) Bending Stiffness vs Disintegration time b) Grammage of the paperboard formed

As we can see from the above plot of bending stiffness vs disintegration time, bending stiffness with disintegration comes out less in comparison to paperboard with dry fibers and no disintegration. This is due to decrease in thickness and bulk of the paperboards after disintegration.

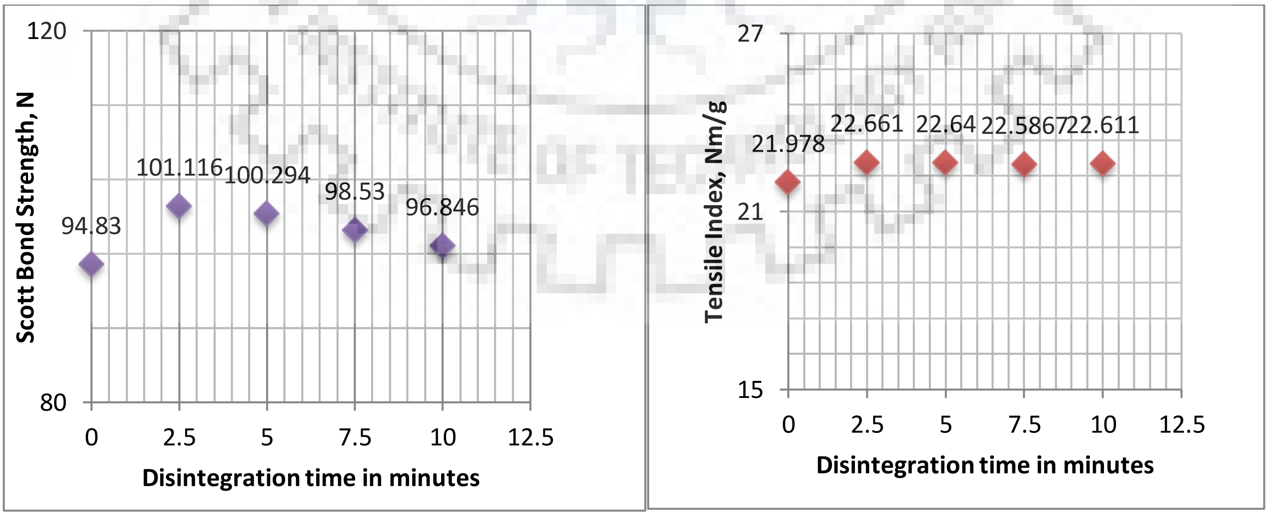
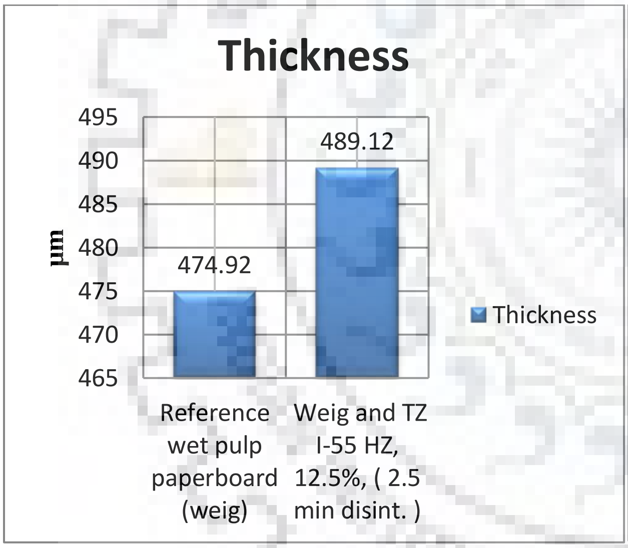


Figure 47 : a) Scott bond Strength Vs Disintegration time, b) Tensile Index Vs Disintegration time.

From the plots of scott bond strength vs disintegration time and tensile index vs disintegration time we see that with disintegration, scott bond strength and tensile index of the paperboard gives larger values as compared to paperboard having dry fibers in the middle layer without disintegration, as with disintegration mean fibril area of dry fibers also increases which creates good bonding between the fibers as compared to fibers without disintegration.

From the above plots we see that at 2.5 minutes of disintegration of dry fibers, bending stiffness decreases by only 2.4% whereas internal bond strength increases by 6.62% and tensile index increases by 3.15% as compared to paperboard with no disintegration and 12.5% fibers in the middle layer.

Therefore we can see that we can improve internal bond strength and tensile strength of multi layered paperboard having dry fibers in the middle layer by means of disintegration operation on dry fibers with much less decrement in bending stiffness. Here is the comparison with reference wet pulped paperboard.



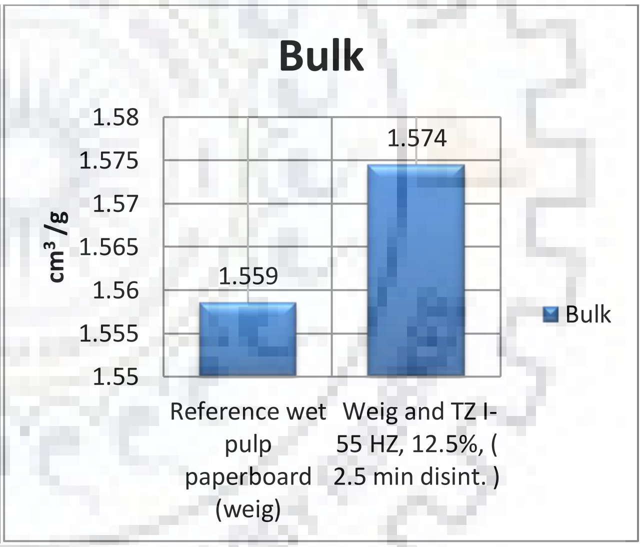


Figure 48 : a) Thickness comparison b) Bulk comparison

Here from the above plots of thickness and bulk we see that for 3 layered paperboard with 12.5% dry fibers in the middle and with 2.5 minutes of disintegration of dry fibers we get improvement of approximately 3 % in thickness and about 1% increment in bulk as compared to 3 layered paperboard made of wet pulped fibres from Weig.

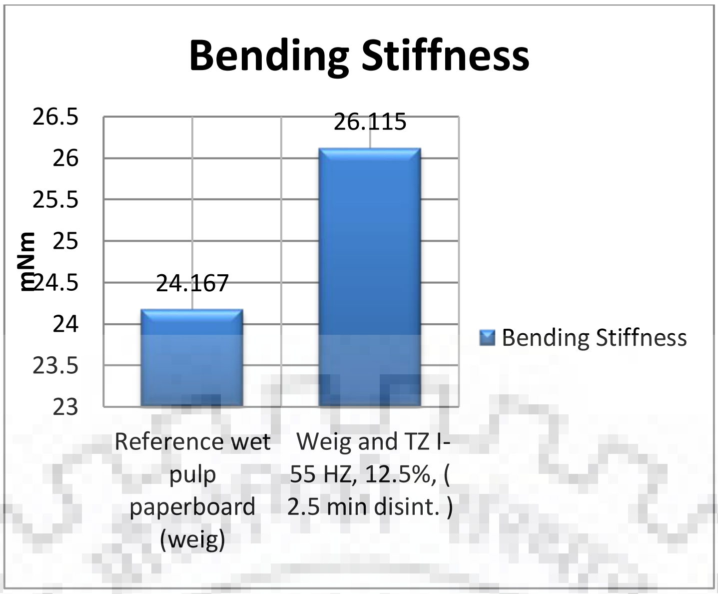
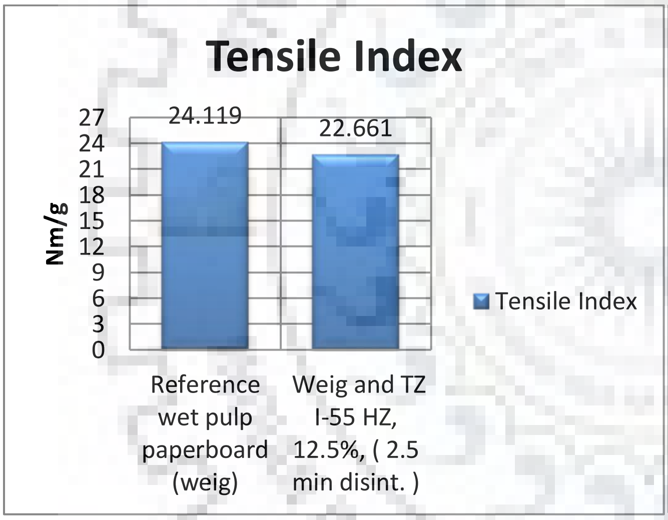


Figure 49 : Bending Stiffness Comparisons



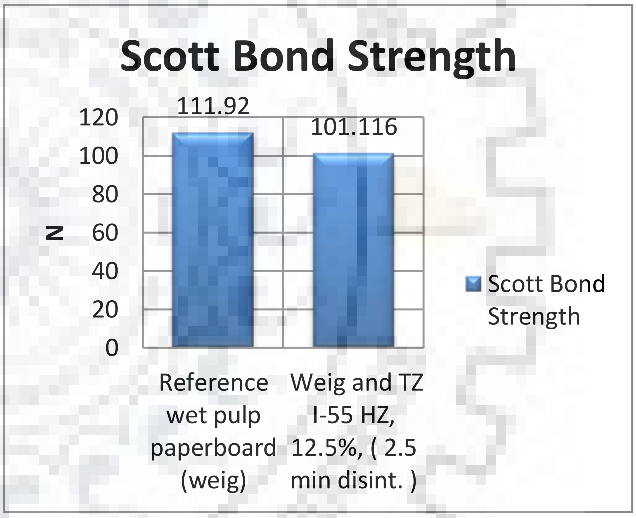


Figure 50 : a) Tensile Index comparison b) Scott Bond Strength comparison

Hence we can interpret from the above graphs that we get increment in bending stiffness of about 8% with very less decrease in strength properties like tensile strength and internal bond strength with the use of disintegration operation on dry fibers in the middle layer.

CHAPTER 5 | CONCLUSIONS

- The Study demonstrated bulk or volume increasing potential of the dry fibers.
- The Study also demonstrated the faster dewatering behavior of dry fibers as compared to conventional wet pulped fibers.
- The bending stiffness however could not always be improved because of dependence of bending stiffness on both thickness as well as modulus of elasticity of the paperboard.
- Furthermore the other strengths properties like internal bond strength and tensile strength were in most cases reduced when dry fibers were used.
- However, it was found that additional short disintegration improves both bulk and stiffness and limits other strength properties reduction to a tolerable level.
- Thus it could be shown that an optimum balance of multilayer paperboard structure (number of layers and grammage of layers, quantity and placement of dry fibers), additional post-treatment like disintegration of dry fibers could improve bulk and stiffness without negative effects on other strength properties.

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