A Study of Alkaline Sodium Sulfite Pretreatment of Spruce During Thermomechanical Pulping

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A STUDY OF ALKALINE SODIUM SULFITE PRETREATMENT OF SPRUCE DURING THERMOMECHANICAL PULPING

by

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A STUDY OF ALKALINE SODIUM SULFITE PRETREATMENT OF SPRUCE DURING THERMOMECHANICAL PULPING

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A review of literature relating sodium sulfite pretreatment during thermomechanical pulping to pulp physical properties revealed many contradictions. Thermomechanical pulping variables were studied for their effect on pulp physical properties. An improvement in pulp physical properties was observed above 1% sodium sulfite treatment. Regression analysis and analysis of variance showed that there was a significant effect of sodium sulfite on the reduction of shive content, pulp brightness, and tear index. Fiber length, tensile, burst, and density were not found to be significantly affected by the amount of sodium sulfite. Sodium sulfite treatment during thermomechanical pulping showed a negative relationship with yield and opacity. Blow pH was not affected by the concentration of sodium sulfite applied at different levels. Sodium sulfite addition reduced the power requirement by about 15% compared to thermomechanical pulping process.
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CHAPTER I

INTRODUCTION

Mechanical pulps are in many ways outstanding raw materials for paper production. Thermomechanical pulping has become an established mechanical pulping technology, with interest being turned towards further improvement. The high energy consumption of the process has initiated various developments with the primary purpose of reducing energy use, but maintaining the high strength and other qualities already achieved. Chemical pre-treatment results in the use of less mechanical energy, but the pulp produced has different properties, particularly reduced opacity, the most important property of mechanical pulps. The objective of this study is to improve the physical properties of the pulps while maintaining the advantages of mechanical pulps such as high yield, printability, low capital investment and low environmental impact.

This study dealt with the chemical pre-treatment of wood chips with sodium sulfite followed by pulping which partly sulfonates the lignin before defibration in a refiner. Sulfonation resulted in permanent fiber softening which not only assists in maintaining fiber quality during the defibration, but was manifested by
increased bonding. In this study alkaline sodium sulfite was used as a pretreatment chemical at different levels. The Sunds Defibrator at Western Michigan University, Kalamazoo was used for this work. The main purpose of this thesis was to determine the sodium sulfite addition level and pH that gave pulps of optimum fiber length and physical properties while minimizing loss of yield and opacity. This study also dealt with the effect of different levels of sodium sulfite on blow pulp pH.

In this work the abbreviation "TMP" will refer to Thermomechanical Pulping and "CTMP" will refer to Chemi thermomechanical Pulping.
CHAPTER II

REVIEW OF LITERATURE

The sulfonation of TMP may improve physical properties pulps but may maintain the quality of mechanical pulps. This literature review will be discussed TMP operating variables, limitations of TMP pulp and sulfonation of TMP as a pre-treatment.

Wood Chemistry

The chemical composition of wood is approximately 50% carbon, 6% hydrogen and 44% oxygen with less than 1% other elements, mostly nitrogen (1). These elements are built up into four classes of wood components; cellulose, the hemicelluloses, lignin and the extractives.

Cellulose is a polysaccharide with a weight-average degree of polymerization between 10,000 and 17,000 (1). It is built from anhydroglucose units connected to each other by β - (1-4)-glucosidic linkages. The molecules are arranged into small building units called microfibrils which have a complex and poorly understood structure (1,2). Cellulose microfibrils are the main structural elements of wood fibers. Cellulose can not be solubilized in water, dilute acids or alkalies at room temperature.
It can be dissolved using cuprammonium hydroxide some salt solutions and some strong acids (3).

Hemicelluloses, also polysaccharides, have a degree of polymerization of 100-200. There are three major types; the xylans, the mannans and the galactans (4). Hemicelluloses, unlike cellulose, are non-crystalline polymers which can largely be extracted from wood using dilute alkalies.

Lignin is an aromatic polymer built from substituted phenylpropane units. Its highly cross-linked structure results from carbon-carbon, and carbon-oxygen bonds through the α, β, γ, 2, 3, 4 and 5 positions of the phenylpropane units. These units are built up in a complex way to form a structure similar to the one proposed by Glasser and Glasser (5).

The wood extractives are non-structural low molecular weight organic and inorganic compounds which are soluble in water or organic solvents or are steam volatile. These compounds include polysaccharides, fatty acids and resins (6).

Softwoods

Softwoods are (on the average) made up of 42% cellulose, 27% hemicellulose, 28% lignin and 3% extractives. Softwoods are to a large extent made up of tracheids. The tracheids are supporting elements that also conduct water in the sapwood. About 95% of softwood
xylem is built from tracheids while the remainder is mostly ray and parenchyma cells. These cells run radially through the tree (1,7). A diagram of a softwood cube is presented in Figure 1. The wall of a typical tracheid is composed of several layers as shown in Figure 2 (8). It consists of the lumen (or center of the cell), secondary wall (by far the most dominant layer), primary wall and middle lamella at the boundary between fibers (8). Figure 3 shows the cell-wall organization with micro-fibrillar textures. The secondary wall is subdivided into further layers (S1, S2, S3). Observations have shown that lignin occurs in the secondary wall of the fibre as well as in the middle lamella. Although the concentration of lignin in the middle lamella (80%) is much higher than the concentration of lignin in the secondary wall (20%), the majority of softwood lignin is actually found in the secondary wall material. For black spruce about 77% of the total lignin exists in the secondary wall whereas only 23% is in the middle lamella (9).

History and Theory of Theromechanical Pulp (TMP)

Mechanical pulp was originally known as groundwood. Charles Fenerty, a Nova Scotian, began experimenting in groundwood pulping, in about 1839. He made the first groundwood paper in the western hemisphere (2). Although
Figure 1. Softwood Cube (2)
Figure 2. Wall of a Typical Tracheid (8)

- Outer surface
- Inner surface
- Inner layer of secondary wall (S3)
- Middle layer of secondary wall (S2)
- Outer layer of secondary wall (S1)

Figure 3. Micro-Fibrillar Textures (8)
modern grinders show many advanced details of construction, their main principle of tearing the fibers out of a log pressed against a grinding stone is primitive and has several drawbacks. One of the main objectives is to overcome the difficulty of separating fibers without damage to the fiber walls. Groundwood pulp therefore gives low strength and requires long-fibered softwoods in the furnish (1).

A more recent development in mechanical pulping involves shredding and grinding chips of wood between the rotating disks of a device called a refiner. The product is known as refiner mechanical pulp and it usually retains more long fibers than stone ground wood and yields stronger paper (8).

TMP is a mechanical pulping process which developed from refiner mechanical pulping. It involves steaming the raw material for a short period at relatively low steaming pressures and refining it when the lignin is soft. In thermomechanical pulping chips are heated to a temperature not exceeding the glass transition point of the lignin where the lignin is softened but remains in the glassy state. In the early stages of TMP development, it was believed that refining below elevated temperatures was fully responsible for the improved pulp qualities.

It is realized today that TMP is a process incorporating two separate steps. The first step is to
preheat the chips with the purpose of softening the lignin. The heating of the chips will soften the lignin which is the binder holding the fibers together, making the fiber more flexible. The softening will allow easier fiber separation without breakage and splintering, resulting in more long fibers and less debris.

Preheating the chips is not sufficient to separate fiber bundles. It is also necessary to fracture the secondary wall of the individual fibers. This second step requires mechanical energy applied to pulp at high consistencies by a refiner. Evidence suggests (10) that wood fibers are stress cycled a large number of times by refiner plate bar to fiber contact or fiber to fiber contact. This compression and decompression generates heat, leading to the production of steam and, eventually, due to fatigue failures, the fibers are released from the wood matrix. The pulp will contain ribbon-like wall segments from the S-1 layer. The quantity of these ribbon-like wall segments is critical, and will greatly affect pulp quality. The quantity of the wall segments found in the final pulp will depend on the refining (1, 10, 11). Latest developments, however, indicate that the temperature inside the refiner can be increased well above the glass transition point, as long as exposure is kept short, i.e., a few seconds, without adverse effect on pulp quality (12).
TMP Operating Variables

In TMP chip quality is often an overlooked important variable. Uniform chip size is critical to assure a uniform feed rate to the refiner. All metering devices are of a volumetric nature; however, uniformity must be maintained gravimetrically. As a result, changes in chip packing density will create uneven gravimetric feed even where uniform volumetric feeding is maintained (10, 13). The moisture content of the chips can be varied within wide limits without any significant influence on energy consumption and pulp properties. However, if the moisture content is below the fiber saturation point, the pulp properties are negatively influenced (10). Chips which are homogeneous in size give the best results regarding pulp properties. Large chips need a longer retention time in the preheater than do the smaller chips. Chip quality is a function of the preheating time required to reach the desired pressure in the preheater (14). Investigations indicated that when chips are fed to a steaming vessel, they will carry air into the vessel. Unless the air is removed by steam purging or by compression, the air will have a profound effect on how rapidly the chips are heated, and the air blanket will prevent access of the steam to the chips, thereby greatly increasing the time needed for heat transfer (10,15). The relationship between air content and temperature with steam pressure as
a parameter is plotted in Figure 4.

Typically the rise of consistency from inlet to outlet is 6-12 percentage points. The development of pulp uniformity during refining is influenced by several variables, the important ones being: (a) amount of pulp present in the refining zone, (b) disc clearance, (c) consumption of refining energy, (d) pressure level during the refining, and (e) inlet consistency.

Water is removed by vaporization during the process. At very high consistencies, the generated heat will dehydrate the fibers and, as a result, they are weak and brittle (16). The effect of consistency between the refiner plates on tear, tensile and brightness is shown in Figure 5.

Evaluation of steaming pressure and its effect on pulp quality indicates that as the steam pressure (and temperature) increase, the tear strength first increases and then decreases. In the case of spruce, a pronounced maximum strength occurred at about 270 kpa as shown in the Figure 6, which when compared to conventional operation at a preheater steam pressure of 220 kpa and a refiner housing pressure of 500 kpa, decreases the hydraulic thrust required to maintain maximum motor load and resulted in an increase in disc clearance. This preheater steam pressure increases the long fiber content of the pulp and improves pulp strength properties with no adverse
Figure 4. Relation of Air Content to Temperature and Pressure in Steam Vessel (10)
Figure 5. Effect of Consistency on (a) Tearing Strength, (b) Burst Strength, (c) Brightness of TMP Pulps. (X = 150 CSF, ▲ = 200 CSF) (10)
Figure 6. Effect of Steaming Pressure on (a) Tearing Strength, (b) Bursting Strength, (c) Scattering Coefficient, and (d) Refining Energy Required in TMP. (X = 150 CSF, Y = 200 CSF) (10)
effect on brightness (17).

A theoretical analysis (18) has shown that changing the differential pressure across a thermomechanical refiner brings about several changes in the conditions within the refining zone. By changing the differential pressure across the pressurized refiner from about +75 to -75 kpa, the result was a reduction in energy consumption of 13-15% while maintaining the same burst strength (18).

Factors Limiting the Strength Properties of TMP

Recently, modifications and improvements in printing technology have resulted in more stringent demands being made on newsprint quality, particularly with regard to sheet consolidation and surface properties. TMP offers definite advantages over other types of mechanical pulps in terms of lower shive levels and superior tearing strength and bonding properties. In the manufacture of newsprint, these pulp quality improvements translate directly into improved web runnability and decreased chemical pulp content, with attendant improvements in sheet opacity and compressibility (19). In newsprint manufacture, the ability of TMP pulp to reduce chemical pulp is not well established because of the problems of lower brightness, opacity, linting and smoothness compared to groundwood (20).

Mohlin (21) confirmed that the large variation in
properties observed among TMP pulps is due both to variations in particle size distribution and to variation in bonding ability of the particles. He concluded that for both the coarse fraction and the middle fraction there exists a large variation in their properties. The coarse fiber variation is due mainly to differences in fiber flexibility. The coarse pulp fraction and the middle fraction is the fiber retained between the 16-30 and 30-200 mesh (in the Bauer McNett), respectively (21).

The fibers and the ribbon-like and fibrillar material make different contributions to pulp strength. The fibers are stiff and cannot bond together in the same way as the fibers of a chemical pulp can. This is reflected in the low strength of the fiber fraction itself. The bonding between the fibers is provided by the conformable ribbon-like fibers and the fibrillar material fraction in the fine fraction.

Sulfonation of TMP

The condition of the exposed fiber surface is an important factor since new surfaces are exposed as the fibers are separated from the parent wood and from each other during the refining operation. The exposed fiber surfaces can be highly lignified, as is the case when the outer cell wall is exposed or when parts of the middle lamella remain attached to the cell wall, or they can be
highly reactive and hydrophilic which leads to the development of good bonding as in the case when the main secondary cell wall is exposed. In the case of chemical treatment, modification of the lignin can occur to such an extent that the original hydrophobic lignin becomes somewhat hydrophilic in character, thus resulting in improved bonding potential (22).

Chemical treatment of TMP improves fiber's cohesiveness and flexibility thus improving strength (21). The most promising method for treatment of TMP can be sulfonation. Sulfonation of lignin appears to be the most economically feasible treatment. It helps to increase pulp strength by chemical modification in contrast to the purely physical changes brought about by alkaline swelling agents. Sulfonation of lignin offers improved fiber flexibility and bonding (23). There are several methods of sulfonation treatments including pretreatment, interstage and post-treatment. Interstage treatment of TMP pulps by sulfonation caused fiber damage during refining action on fibers which have already been separated. This results in some loss in tear strength, but the damaged fibers and removed fiber walls produce a pulp with larger surface area, which is required for printing quality (24).

Chemical pretreatment gives the following advantages compared to normal TMP (25).
1. Chemical pretreatment leads to more selective fiber separation. This results in a higher long fiber content and dramatically lower shive content compared to TMP.

2. Pretreatment with sodium sulfite gives pulps with better fiber flexibility than pure TMP. This manifests itself in higher sheet density and improved tensile index and burst index.

3. Pretreatment with sodium sulfite gives pulps with higher brightness than TMP as well as a better pulp bleachability.

4. Resins can readily be removed during sulfonation of TMP, making the pulps suitable for absorbent grades.

Chemistry of Sulfonation

CTMP processing of spruce wood with sodium sulfite under mild conditions was studied by analysis of a corresponding effluent, consisting of 30% lignin and 35% saccharides in the dissolved organic matter (26). The influence of wood chip impregnation with sodium sulfite stabilizes glucosidic bonds of neutral polysaccharides toward a hydrolytic cleavage. The main saccharide component of the effluent is glucuronoxylan. Kosikova and Joniak (26) stated that the introduction of sulfonate-groups into lignin under conditions of CTMP production caused its partial dissolution and some change of
residual lignin in the pulp, particularly its high solubility both during acid and alkali hydrolysis of the pulp. He also stated that the properties of CTMP lignin are very similar to those of lignin in neutral sulfite semi-chemical pulps. According to a model experiment, approximately 50% of lignin-saccharidic bonds of the benzyl-ether type were cleaved under sodium sulfite action accompanied by formation of α-sulfonic acid from the liberated p-hydroxybenzyl alcohol component.

The sulfonation reaction is shown in Figure 7. As a consequence of hydrolytic and sulfonation reactions, CTMP effluents contain sulfonated lignin[10]. The relative concentrations of sulfur dioxide, hydrogen sulphite and sulfite are governed by the pH of the solution as shown in the Figure 8. As can be seen, sulfur dioxide is present almost exclusively in the form of hydrogen sulfite ions at pH around 4[9]. Below and above this value the concentrations of sulfur dioxide and sulfite ions, respectively, are increased. These equilibria also vary with the temperature. At temperatures used for pulping (130-150 °C), the actual pH value is higher than that measured at room temperature and this shift in pH is larger in the acidic region. Sodium sulfite is easily soluble and the use of this base has not limited by the pH of the cooking liquor [9, 27].
Figure 7. Sulfonation Reaction (10)

Figure 8. Effect of pH on the Molar Ratio of Hydrogen Sulfite ion and Sulfur Dioxide (9)
Figure 9 shows the ionization difference spectra between TMP-lignin-hemicellulose complex and CTMP-lignin-hemicellulose complex. The obtained results led to a conclusion that some of lignin-carbohydrate linkages were cleaved to a certain extent in CTMP system under investigation (26).

Comparison of Pulp Properties During Sulfonation of TMP

Sinkey (28) stated that the response of spruce to sulfonation is superior when compared with that of resinous, high-density woods. Sulfonation rate, yield and brightness are affected by pH. The extent of the increase in fibre flexibility and bonding is determined by the extent of sulfonation above a certain minimum; hence time, temperature and sulfite concentration are key determinants of pulp properties. He also stated that the wood pretreatments generally afford the best tear-tensile; sulfonation of defibred pulp has advantages for linting, wet web strength, light scattering and certain energy bonding relationships (28).

Engstrand, Hammar, and Htun (29) said that an increase in temperature and an increase in sodium sulfite concentration increased initial reaction rate. The mechanism of the influence of pH at different sodium sulfite concentrations in the alkaline region is at present not clear. Ferritsius and Moldenius (31) compared...
Figure 9. The Ionization Difference Spectra (12)
four methods of impregnation of chips; spray impregnation, steaming followed by soaking in cold sulfite liquor, plug screw impregnation and refiner addition. They concluded that the addition of sulfite before the preheater gave pulps with a low shive content and good strength properties at a freeness level of 136 ml CSF. They also believed that these improved properties may be due to rapid diffusion of sulfite into the chips. They stated that when the time between impregnation and preheating was reduced to 30 minutes, 25% of the sodium sulfite charged was chemically bound to the pulp. It was also concluded that approximately 80% of the sulfonation occurred during the preheating, 15% during the refining and 5% after the refining. The sulfonation during and after refining was caused by residual sulfite in the pulp.

Attack, Heinter, and Stationevala (32) have studied the treatment of black spruce chips with sodium based sulfite solutions in the pH range of 1.8 to 9.8 by CMP and CTMP methods. They concluded that the increase in degree of sulfonation reduced the fines content in the pulp produced by CTMP at a given specific energy. They also found that this pretreatment promoted fiber collapse and hence increased fiber bonding. These combined effects led to a decrease in specific scattering coefficient. They also observed that the breaking length and density of CMP and CTMP were increased above a level of about 1%
sulfonation. Cummerus and Kurra (33) have studied the low (4-5 %) and high (16-20%) sodium sulfite pretreatments of mechanical pulp in the laboratory. They concluded that the low sulfite treatment resulted in the same relationship between freeness and specific energy consumption as high sulfite treatment. They also indicated that the low sulfite treatment was sufficient to change the fiber liberation process in the refining stage.

Attack and Heitner (34) found that when eastern black spruce was subjected to mild treatment its softening temperature and elastic shear modulus decreased. They concluded that the decrease of each of these properties was a linear function of increasing sulfonate content above approximately 2 percent.

Sinkey and Charters (35) have studied a variety of chemical pretreatments during TMP. They observed significant improvements in the pulp brightness and bonding strength with softwood TMP when 6-10% sodium sulfite or bisulfite was added to the eye of the pressurized refiner. Costantino and Fisher (36) found that addition of sodium sulfite to the TMP system increased the brightness of pulp to the extent that the sodium hydrosulfite brightening step was not required.

Axelson and Simonson (37) have studied chips preheated for 10 minutes in atmospheric pressure, followed by 10 minutes cold impregnation with sodium sulfite
liquor, and finally preheated at 126°C for 3 minutes. They concluded that the method resulted in a very efficient impregnation with a high degree of utilization of the sulfite added. Optimum strength properties were achieved with a minimum of energy input and retained the good optical properties of mechanical pulp. These results with respect to pulp quality and energy requirements were obtained at varying sulfite additions. Their results indicated the sulfur content (as wt.-% sodium sulfite on the dry pulp) level must be carefully chosen for maximum tensile strength and light scattering coefficient at a given energy input.

Tantlo and Hardy (38) stated that the chemical addition rate of sodium sulfite for TMP, generally in the range of 2 to 5 percent based on oven dry wood. Celleco (40) stated that the chemical softening of lignin by the addition of sodium sulfite prior to defibration is a very delicate matter if optimum strength properties are to be achieved with a minimum of energy input while retaining the good optical properties of a mechanical pulp. He found that when the spruce chips were thoroughly impregnated in the preheater, that the chemical reactions that occurred, along with the irreversible stiffness drop obtained on heating. It also strongly affected critical wood softening, defibration, and fibrillation obtained in the refiner. Mokvist, Jackson, and Ruvo (39) impregnated
chips with a 1-5\% sodium sulfite solution levels at a pH of 9 to 12 and preheated at normal TMP conditions. They found unbleached pulp yields for softwood in the range of 91\% to 96\% depending on the chemical application level. They also found five points of pulp brightness improvement at the 4\% charge of chemical.

Kojima and Kayama (41) stated that the chips which were treated with alkaline sulfite were defibrated in the fibre wall, whereas the chips treated with neutral bisulfite were defibrated in the middle lamella in the refining stage. Kurra, Virkola, and Lindholm (42) found that if untreated areas were present in the chips, the shive content increased rapidly and the energy consumption decreased. Laliberte, Shallborn, and Karnis (43) stated that the mild sulfonation of spruce and pine chips to a sulfonate content of 0.5\% increased sheet density and dry strength properties of pulps and reduced shive and minishive content.

Overall comparison of all these studies showed the improvement of brightness and strength properties by the addition of sodium sulfite as a pretreatment chemical during TMP. Some of these studies also showed the reduction of shive content, loss in pulp yield and loss in opacity.
CHAPTER III

PRESENTATION OF THE PROBLEM

The review of the literature has shown that many studies have been done on the sulfonation of TMP by different methods. There are several methods of sulfonation treatments including pretreatment, interstage, and post treatments. The review of literature has indicated that the advantages of the chemical pretreatment for TMP is a more effective means of sulfonation compared to interstage and post treatment (24) (25) (31).

For chips impregnated in sodium sulfite solution at room temperature and then defibered (CTMP) laboratory studies (32) (33) (34) (35) have shown improved the unbleached pulp brightness, strength properties, and fiber length compared to TMP. These laboratory results were also supported by pilot plant studies (37) (40).

However, in order to impregnate chips (pretreatment) with sodium sulfite in a continuous process, the sulfite liquor should ideally be added to the chips as they enter the preheater rather than the eye of the refiner. This would provide additional impregnation time and reduced power requirements as well as increased unbleached brightness which will result in greater bleached brightness.
Impregnation with sodium sulfite in the preheater (steam tube) has not been studied in a continuous process. It is the purpose of this investigation to compare this method of impregnation (pretreatment) with interstage and post treatment.

In this study the effect of the percentage of sodium sulfite on the chips will be varied over the range of 0-4 percent. Pulp properties to be measured are freeness, fiber length, unbleached brightness, opacity, shive content, tensile, tear, and burst.

Data obtained will be compared to data from the literature on impregnation at room temperature before defibering and pretreatment using a laboratory digester.

The development of pulp properties will be studied through the use of regression analysis.
CHAPTER IV

EXPERIMENTAL

Summary of Experimental Design

It was intended that this study of sodium sulfite addition during TMP should have practical application in the pulp and paper industry. The experimental work will be done as much as possible under typical machine operating conditions of the TMP system. All of the experimental pulps will be produced using the Sunds Defibrator in the pilot plant operated by the Department of Paper and Printing Science and Engineering at Western Michigan University.

Trial Runs for TMP Operating Parameters

To achieve the ultimate goal of this study, the initial trials runs were designed and carried out. This will be done to find the optimum TMP system operating conditions by changing the following variables:

1. Presteaming time and temperature for chips.
3. Cooking time in the preheater
4. Cooking temperature in the preheater
5. Disc clearance for flat and conical zones.
6. Amount of infeed dilutions to the refiner zones.
7. Percentage of power applied in the refiner.

Initial runs were used to calculate the approximate yield, cooking time, and energy consumption.

Study of Variables

Energy Input

To study the power input of TMP process pulps were produced by varying the power from 20% to 55% to reach the desired freeness at the same production rate. At the lower power applied, the Mead laboratory refiner and Valley beater were used to get the desired freeness. The actual power input to the defibrator for this study was about 40% to 45% of the total power of 200 HP.

Disc Clearance

In the initial studies TMP pulps were produced at different disc clearances, the flat zone varied from 0.90 mm to 0.45 mm and the conical zone from 0.60 mm to 0.25 mm. Disc clearance for this study was about 0.45 mm for the flat zone and 0.25 mm for the conical zone.

Percentage of Sodium Sulfite

In the initial experiments TMP pulps were produced with and without water at the impregnator. Ten percent of water at the impregnator was set for this study. The
percentages of sodium sulfite for this study were 1.0, 2.0, and 4.0 on the basis of O.D chips.

Liquor pH and Blow Pulp pH

The liquor pH was measured and adjusted to the desired pH by using dilute 10% sulfuric acid and 10% sodium hydroxide.

Blow pH was measured for the TMP pulp and also CTMP pulps which were produced at the different percentage addition rates of sodium sulfite and liquor pH as per Tappi Method T-509 (Appendix D).

Approximate Yield Determination

In this study the yield of pulp was calculated as follows:

For TMP pulp yield, \% = \[ \left( \frac{X \times A}{Y(100-B)} \right) \times 100 \]

where

- X = Pulp production rate kgs. /min.
- A = Consistency of blow pulp
- Y = Chip feed rate kgs. /min.
- B = Chip moisture

For CTMP yield, \% = \[ \left( \frac{X \times A}{Y(100-B) + S} \right) \times 100 \]

where S = Sodium sulfite addition rate kgs. /min.

Power Consumption

In this study the power consumption was defined as:

Power Consumption (HPD/ODT) = \[ \frac{\left( P/100 \times 200 \right) - 20}{T} \]
where \( \text{HPD/ODT} = \text{Horse power days per oven-dry ton} \)

\[ P = \text{Percentage of power applied} \]

\[ T = \text{Production rate OD ton/day} \]

\[ 200 = \text{Total power of the refiner in HP} \]

\[ 20 = \text{No load power of the refiner in HP}. \]

**Fiber Length Distribution and Shive Content**

The Kajaani Fiber Length Analyzer was employed to investigate the fiber length distribution of TMP and CTMP pulps. A laboratory vibrating flat screen with six-cut (0.006" opening) was used to determine the shive content of the TMP and CTMP pulps.

Table 1 shows the variables which were studied in the six runs of experimentation. All the operating parameters which were used for different runs in this study are presented in Appendix F.

**Experimental Materials and Preparation**

The wood chips used in this study were mixed spruce softwood chips from northern Michigan, which were donated by American Fibrit Inc., Battle Creek, MI. These were stored in barrels to minimize the moisture variation. The chip classification report and wood chip sample figure are in the Appendix B.

Sodium sulfite solution preparation and concentration determination is given in the Appendix C. The system that
was used to produce TMP and CTMP pulps is shown in the schematic diagram (Figure 10).

Table 1
Variables Investigated

<table>
<thead>
<tr>
<th>Variable</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium sulfite addition, %</td>
<td>0/4</td>
<td>0/4</td>
<td>0</td>
<td>0/2/4</td>
<td>0</td>
<td>0/1/2</td>
</tr>
<tr>
<td>Presteaming time, min</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Water in impregnator</td>
<td>no</td>
<td>no/yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Preheater pressure, psi</td>
<td>35</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Reaction time, min.</td>
<td>12</td>
<td>10/12</td>
<td>10</td>
<td>10</td>
<td>10/12</td>
<td>10</td>
</tr>
<tr>
<td>Power input (HPD/ODT)</td>
<td>28.5</td>
<td>52.0</td>
<td>75.0</td>
<td>61/53</td>
<td>nil</td>
<td>62/53</td>
</tr>
<tr>
<td>Secondary refining</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Clearance:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat zone, mm</td>
<td>.85-.90</td>
<td>.6-.7</td>
<td>.45-.5</td>
<td>.50</td>
<td>.25</td>
<td>.4-.45</td>
</tr>
<tr>
<td>CD zone, mm</td>
<td>.60-.65</td>
<td>.4-.45</td>
<td>.25-.3</td>
<td>.25</td>
<td>.35</td>
<td>.25-.3</td>
</tr>
</tbody>
</table>

Sunds Defibrator Flow Description

The chips are initially added to the infeed hopper and presteamed. Between the hopper and the preheater the chips travel in a plug screw where severe compression occurs. The chips swell when released into the
Figure 10. Schematic Diagram of Sunds Defibrator
pressurized preheater. At this point liquor may be added for excellent absorption. A series of screws carry the chips from the preheater to the refiner where defibration takes place. The blowline allows the pulp to travel from the refiner casing to an atmospheric cyclone discharge. For this work, the point of liquor addition was the Impregnator.

All the collected pulps samples of TMP and CTMP were diluted in the slush maker to 2% consistency and disintegrated for 5 minutes at 140°F to remove latency as per Tappi Method T-262(Appendix D).

Operational Problems of the Sunds Defibrator

The experimental data were limited by the following operational problems of the Sunds Defibrator:

1. The ventilation system for the room housing the Sunds Defibrator was improperly adjusted and set off the fire alarm system two times during the trials. This produced limited data during two planned trials.

2. When the ventilation system was repaired, the defibrator flat zone plates broke and disabled the refiner.

3. The Sunds Defibrator company was unable to provide a new set of plates for the refiner in the time remaining for further experiments required to replicate the data generated.
Data Management

The data from the experiments were analyzed by two statistical methods:

1. Simple regression analysis was used to estimate the fiber length, shive content and pulp physical properties at a given percent of sodium sulfite addition. It was also used to generate correlation coefficients and R-square values.

2. Analysis of variance was applied to determine the significance of independent variables on the fiber length, shive content, and pulp physical properties.

Graphs were plotted for pulp freeness, fiber length, yield, and strength properties against the different percentages of sodium sulfite for runs 4 and 6.
CHAPTER V

PRESENTATION OF RESULTS AND DISCUSSION

The following data analysis illustrates the effects of TMP operating parameters and the potential of sulfonation of TMP to improve the fiber length, pulp physical properties, and reduction of shives content compared with the TMP pulps. The analysis of variance (ANOVA) and regression analyses were applied in this presentation and discussion section.

Initial Runs of TMP

Initially two runs were made to determine the operating parameters. Pulp samples were not collected for these runs. It was found that a presteaming time for chips of about 10 minutes avoided the plugging of the infeed screw feeder and loss of pulp brightness. These runs were also used to calculate the reaction time in the preheater. They were also used to determine the yield by maintaining a constant level in the preheater. These runs were given a range of infeed dilutions to the refiner to avoid plugging of the blowline and the dehydration of the fibers.
Secondary Refining

Table 2 shows the improvement of CTMP Pulp properties of brightness, tensile, and burst are 11.5%, 44.1%, and 75.3% respectively in comparison to TMP pulp properties. Reduction of shives content (59.5%) and loss of opacity (0.66%) also occurred. These results were obtained when Mead refiner was used as a secondary refiner to get the required freeness.

Table 2
Run 1 Pulp Physical Properties of TMP and CTMP (4% Sodium Sulfite) With Mead Refiner

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP</th>
<th>CTMP</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refining time in</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Mead refiner, min.</td>
<td>3</td>
<td>3</td>
<td>-3.75</td>
</tr>
<tr>
<td>Freeness, ml.</td>
<td>213</td>
<td>205</td>
<td>-3.75</td>
</tr>
<tr>
<td>Shives content, %</td>
<td>2.54</td>
<td>1.03</td>
<td>-59.5</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>39.8</td>
<td>44.4</td>
<td>+11.5</td>
</tr>
<tr>
<td>Opacity, %</td>
<td>97.2</td>
<td>96.5</td>
<td>-0.66</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>13.2</td>
<td>19.1</td>
<td>+44.1</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.465</td>
<td>0.815</td>
<td>+75.3</td>
</tr>
<tr>
<td>Tear Index</td>
<td>2.54</td>
<td>2.47</td>
<td>-2.64</td>
</tr>
</tbody>
</table>

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When the Valley beater was used as a secondary refiner, there was little change in pulp properties as compared with Mead refiner and the results are given in the Table 3. The Valley beater was not practical as a secondary refiner because of a foam problem and time consumption. It was also found that there was loss of fibers along with the foam which caused differences in pulp properties compared to the Mead refiner (see Table 3). The Mead refiner was preferred for secondary refining in the laboratory.

Table 3
Run 1 Pulp Physical Properties of TMP and CTMP (4% Sodium Sulfite) With Valley Beater

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP</th>
<th>CTMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beating time in Valley beater, min.</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>Freeness, ml.</td>
<td>218</td>
<td>210</td>
</tr>
<tr>
<td>Shives content, %</td>
<td>2.94</td>
<td>1.83</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>38.6</td>
<td>42.9</td>
</tr>
<tr>
<td>Opacity, %</td>
<td>94.7</td>
<td>96.1</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>16.3</td>
<td>17.4</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.617</td>
<td>0.719</td>
</tr>
<tr>
<td>Tear Index</td>
<td>2.81</td>
<td>4.22</td>
</tr>
</tbody>
</table>

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Effect of Water Addition to the Impregnator

Table 4 indicates the improvement of pulp strength properties with addition of water to the Impregnator. It appeared to produce more uniform moisture content in the chips before defibration. This water addition reduced the fiber damage slightly when the chips were compressed. This was evident as shown by the improvement of strength properties of the resulting pulp.

Run 2 also showed CTMP pulp had improved strength properties compared to TMP pulp, but brightness was decreased about 6% points. This was caused by insufficient flow of sodium sulfite which resulted in non-uniform impregnation. The liquor flow loop was to be recalibrated for the next experimental run. In this run the refiner load was increased to 52 HPD/ODT.

Limitation of Power Input

When power input was increased from 52 to 75 HPD/ODT, the TMP pulp brightness and tensile and burst index were decreased as shown in the Table 5. The reduction in brightness and strength properties shows a possibility of fiber damage and fines generation in the system. It also shows that the increase in refining energy increased the tear index of pulp. This results shows that a possible cause of fiber cutting action during refining, as compared to fiber fibrillation.
Table 4

Run 2 Pulp Physical Properties of TMP1, TMP2, and CTMP (4% Sodium Sulfite)

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP1</th>
<th>TMP2</th>
<th>CTMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refining time in Mead refiner, min.</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Freeness, ml.</td>
<td>265</td>
<td>257</td>
<td>170</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>36.7</td>
<td>36.1</td>
<td>29.0</td>
</tr>
<tr>
<td>Opacity, %</td>
<td>96.2</td>
<td>96.3</td>
<td>94.2</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>7.50</td>
<td>8.40</td>
<td>14.6</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.295</td>
<td>0.420</td>
<td>0.617</td>
</tr>
<tr>
<td>Tear Index</td>
<td>1.35</td>
<td>1.80</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Note: TMP1 = No water to Impregnator, TMP2 = water to Impregnator

Table 5

Run 3 Pulp Physical Properties of TMP

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP(Run 2) (52 HPD/ODT)</th>
<th>TMP(Run 3) (72 HPD/ODT)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeness, ml.</td>
<td>257</td>
<td>180</td>
<td>-42.7</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>36.1</td>
<td>32.5</td>
<td>-11.1</td>
</tr>
<tr>
<td>Opacity, %</td>
<td>96.3</td>
<td>96.4</td>
<td>+0.110</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>8.40</td>
<td>6.60</td>
<td>-27.3</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.420</td>
<td>0.350</td>
<td>-20.0</td>
</tr>
<tr>
<td>Tear Index</td>
<td>1.80</td>
<td>2.10</td>
<td>+14.3</td>
</tr>
</tbody>
</table>
Effects of Percent of Sodium Sulfite

In run 4 (Table 6), percentage of sodium sulfite was varied to 0, 2, 4 at pH 9 and power input held constant for TMP at 61 HPD/ODT and CTMP at 52 HPD/ODT. The pulp physical properties are shown in Table 6.

Table 6
Run 4 Pulp Physical Properties of TMP, CTMP2, CTMP4

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP</th>
<th>CTMP2</th>
<th>CTMP4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeness, ml</td>
<td>380</td>
<td>357</td>
<td>470</td>
</tr>
<tr>
<td>Fiber length, mm</td>
<td>1.57</td>
<td>1.60</td>
<td>1.68</td>
</tr>
<tr>
<td>Yield, %</td>
<td>94.6</td>
<td>94.0</td>
<td>91.2</td>
</tr>
<tr>
<td>Shive content, %</td>
<td>3.43</td>
<td>3.03</td>
<td>2.65</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>35.3</td>
<td>37.7</td>
<td>41.6</td>
</tr>
<tr>
<td>Opacity, %</td>
<td>96.9</td>
<td>95.8</td>
<td>91.2</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>5.80</td>
<td>8.50</td>
<td>9.2</td>
</tr>
<tr>
<td>Tear Index</td>
<td>2.34</td>
<td>3.70</td>
<td>4.2</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.284</td>
<td>0.354</td>
<td>0.402</td>
</tr>
<tr>
<td>Density</td>
<td>0.314</td>
<td>0.326</td>
<td>0.327</td>
</tr>
</tbody>
</table>

Note: CTMP2 = 2% Sodium Sulfite, CTMP4 = 4% Sodium Sulfite

The experiment was repeated in run 6, but used 0, 1, and 2 percent of sulfonation at pH 9 with same energy input, and results are presented in the Table 7. Blow
pulp pH was measured for TMP and CTMP pulps in this experimental run. The blow pulp pH was not affected with different percent of sodium sulfite as shown in the Table 6. It was probably due to the small quantity of liquor added to the chips.

Table 7
Run 6 Pulp Physical Properties of TMP, CTMP1, CTMP2

<table>
<thead>
<tr>
<th>Properties</th>
<th>TMP</th>
<th>CTMP1</th>
<th>CTMP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blow pulp pH</td>
<td>7.1</td>
<td>6.9</td>
<td>7.1</td>
</tr>
<tr>
<td>Freeness, ml</td>
<td>210</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Fiber length, mm</td>
<td>1.61</td>
<td>1.62</td>
<td>1.70</td>
</tr>
<tr>
<td>Yield, %</td>
<td>95.6</td>
<td>95.2</td>
<td>94.7</td>
</tr>
<tr>
<td>Shive content, %</td>
<td>4.10</td>
<td>3.90</td>
<td>3.75</td>
</tr>
<tr>
<td>Brightness, %</td>
<td>34.0</td>
<td>34.9</td>
<td>35.8</td>
</tr>
<tr>
<td>Opacity</td>
<td>96.7</td>
<td>96.0</td>
<td>95.4</td>
</tr>
<tr>
<td>Tensile Index</td>
<td>7.8</td>
<td>8.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Tear Index</td>
<td>2.8</td>
<td>3.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Burst Index</td>
<td>0.380</td>
<td>0.375</td>
<td>0.405</td>
</tr>
<tr>
<td>Density</td>
<td>0.314</td>
<td>0.326</td>
<td>0.327</td>
</tr>
</tbody>
</table>

Note: CTMP1 = 1% Sodium Sulfite, CTMP2 = 2% Sodium Sulfite
Run 4 and run 6 pulp physical properties were regressed to determine the correlation coefficient and R-square values. Regression equations are presented in the Appendix G. Analysis of variance was applied to find the significance of percent sodium sulfite on pulp physical properties. Because of fewer data points the regression and variance analysis may not be strong enough for practical applications.

F-value must be greater than 39.9 for the F-distribution to be significant at a 10% level of significance.

**Pulp Freeness and Fiber Length**

**Table 8**

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.7535</td>
<td>56.78</td>
<td>1.314</td>
<td>0.4567</td>
</tr>
<tr>
<td>6</td>
<td>0.9607</td>
<td>92.31</td>
<td>12.00</td>
<td>0.1789</td>
</tr>
</tbody>
</table>

From Table 8 and Table 9, correlation coefficient and R-square values show that the pulp freeness and fiber length are correlated with the percent of sodium sulfite,
but these were not significant at 10% level of significance. Figure 11 and Figure 12 also show the correlation in both runs. Due to increase in sodium sulfite addition (0-4%), the fiber length was increased from 1.57 mm to 1.68 mm. Cummerus and Kurra (33) found similar increase of fiber length (1.21 to 1.69) at the same level of sodium sulfite addition. Reduction of fines content was observed as sodium sulfite increased which can the cause of an increase in freeness. The Kajaani fiber length distributions are given for 0, 2, and 4% sodium sulfite addition in Appendix H. These results showed the reduction of fines content by the addition sodium sulfite.

Table 9
Correlation Coefficient, R-Square, F-Value F-Probability Relating Percent Sodium Sulfite to Fiber Length

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.9707</td>
<td>94.28</td>
<td>16.333</td>
<td>0.1544</td>
</tr>
<tr>
<td>6</td>
<td>0.9122</td>
<td>83.22</td>
<td>12.00</td>
<td>0.2687</td>
</tr>
</tbody>
</table>

Pulp Yield

Pulp yield has negative relationship with the percent of sodium sulfite as shown in Table 10 and Figure 13. In
Figure 11. Effect of Sodium Sulfite on Freeness
Figure 12. Effect of Sodium Sulfite on Fiber Length
Figure 13. Effect of Sodium Sulfite on Pulp Yield
run 6 sodium sulfite addition has a significant effect on the pulp yield. In this study pulp yield was 94.6 to 91.2%, depending on the sodium sulfite application level, i.e., 0-4%. Mokvist et al. (39) found similar pulp yield results (96 to 91%) with 1-5% sodium sulfite addition levels.

Table 10
Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Pulp Yield

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-0.9633</td>
<td>92.79</td>
<td>12.873</td>
<td>0.1703</td>
</tr>
<tr>
<td>6</td>
<td>-0.9979</td>
<td>99.59</td>
<td>243.00</td>
<td>0.0408</td>
</tr>
</tbody>
</table>

Shive Content

The shive content was negatively correlated with the percent sodium sulfite in both cases as shown in Table 11 and Figure 14. Shive content had a significant effect at all levels of sulfite treatment. As expected the shive content decreased with increased sulfite treatment. In run 4, shive content was reduced from 3.43% to 2.65% with addition of 4% sodium sulfite during TMP. The study of Laliberte et al. (43) showed the reduction of shive content from 4.65% to 1.10% during sulfonation of TMP.
Figure 14. Effect of Sodium Sulfite on Shive Content
Table 11

Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Shive Content

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>- 0.9998</td>
<td>99.98</td>
<td>4563.00</td>
<td>0.00942</td>
</tr>
<tr>
<td>6</td>
<td>- 0.9966</td>
<td>99.32</td>
<td>147.00</td>
<td>0.0523</td>
</tr>
</tbody>
</table>

Brightness and Opacity

In Table 12 the correlation coefficient and R-squares values indicate a definite relationship between pulp brightness and the percent of sodium sulfite. This is also supported by Figure 15. In both the runs brightness was significantly affected by the addition of sodium sulfite. At the same time opacity was negatively related with the percent sodium sulfite as shown in the Figure 16 and Table 13. An increase in sodium sulfite from 1 to 2% caused a pronounced increase in the pulp brightness. Because of increase in sodium sulfite addition (0-4%), the brightness was increased 6 points. Around 2 points of brightness was gained with addition of 2% sodium sulfite. At the same time opacity was reduced (96.9 to 91.2 %) with the increase of sulfite addition (0-4%). Mokvist and Jackson found similar increase of brightness around 2 and 5 points.
Brightness vs Percent Sodium Sulfite

Figure 15. Effect of Sodium Sulfite on Brightness
Figure 16. Effect of Sodium Sulfite on Opacity
with addition of sodium sulfite 2% and 4% respectively.

Table 12

Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Brightness

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.9893</td>
<td>97.86</td>
<td>45.76</td>
<td>0.09343</td>
</tr>
<tr>
<td>6</td>
<td>1.000</td>
<td>100.00</td>
<td>9999.99</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table 13

Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Opacity

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>- 0.9988</td>
<td>99.77</td>
<td>432.00</td>
<td>0.0306</td>
</tr>
<tr>
<td>6</td>
<td>- 0.9990</td>
<td>99.80</td>
<td>507.00</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

Pulp Strength Properties

From Table 14 and Table 15 it can be seen that the tensile index and tear index correlation with the percent of sodium sulfite. Figure 17 and Figure 18 also support the tensile and tear relationship with increasing percent
Figure 17. Effect of Sodium Sulfite on Tensile
Figure 18. Effect of Sodium Sulfite on Tear
addition of sodium sulfite. Tensile index was not a significant effect at the 10% level of significance, but tear index was significant in run 6. Improvement of tensile and tear indicates that it is quite possible that the fibers were well fibrillated. It also indicated the possibility of improvement in bonding strength as the percent of sodium sulfite was increased.

Table 14
Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Tensile Index

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.94685</td>
<td>89.66</td>
<td>8.67</td>
<td>0.2084</td>
</tr>
<tr>
<td>6</td>
<td>0.9522</td>
<td>90.67</td>
<td>9.72</td>
<td>0.1976</td>
</tr>
</tbody>
</table>

Table 15
Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Tear Index

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.9662</td>
<td>93.35</td>
<td>14.03</td>
<td>0.1660</td>
</tr>
<tr>
<td>6</td>
<td>0.9933</td>
<td>98.68</td>
<td>75.00</td>
<td>0.0732</td>
</tr>
</tbody>
</table>

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In run 6, tensile index increased 23% with addition of 2% sodium sulfite. It was also found the same increased 55% with 4% sodium sulfite addition in the run 4. Gummerus and Kurra (33) found similar increase of tensile index 38% with the same level of addition. Axelsson and Simonson (37) indicated the tensile index increased about 12% with 1% sulfur content.

Tear index increased from 2.34 to 4.2 with addition of 4% sodium sulfite. Gummerus and Kurra (33) found similar increase of tensile index from 5.06 to 7.31 at the same level of addition.

Burst index and density also increased with increasing percent sodium sulfite as shown in the Table 16 and Table 17. Level of sodium sulfite did not significantly affect the burst index and density of the pulp.

Table 16
Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Burst Index

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.7535</td>
<td>56.78</td>
<td>1.314</td>
<td>0.4567</td>
</tr>
<tr>
<td>6</td>
<td>0.7777</td>
<td>60.48</td>
<td>1.530</td>
<td>0.4327</td>
</tr>
</tbody>
</table>
Table 17
Correlation Coefficient, R-Square, F-Value, and F-Probability Relating Percent Sodium Sulfite to Density

<table>
<thead>
<tr>
<th>Run</th>
<th>Correlation Coefficient</th>
<th>R-Square</th>
<th>F-Value</th>
<th>F-Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.8940</td>
<td>79.94</td>
<td>3.984</td>
<td>0.2957</td>
</tr>
<tr>
<td>6</td>
<td>0.5406</td>
<td>29.23</td>
<td>0.4129</td>
<td>0.6363</td>
</tr>
</tbody>
</table>

Power Input

The energy input was decreased about 9 HPD/ODT in run 4 and run 6 with increasing percent sodium sulfite. As expected, the energy input was decreased when sulfite levels were above 2%.

In run 5, it was found that the flat zone clearance must be more than the conical zone to increase the power to the refiner. The disintegration of chips takes place in the flat zone and if the clearance is less than the conical zone there is a higher chance of plugging the refiner. Since the chips have already been disintegrated in the flat zone, the clearance in the conical zone was kept lower to improve refining and increase the energy imparted to the pulp.
CHAPTER VI

SUMMARY OF RESULTS

The effect of sodium sulfite as a pretreatment chemical under pressurized impregnation in TMP clearly showed an increase in long fiber content, brightness, and strength properties of the pulp.

Initial experimentation gave the range of TMP operating parameters needed to get good quality pulp. In the laboratory, the Mead refiner was used as secondary refiner to get the required freeness. It was more suitable than the Valley beater for this study. Ten percent water added to the impregnator improved tensile index 12%, burst index, burst index 30%, and tear index 22% for TMP pulp compared to no water addition. This was due to more uniform moisture in the chips before defibering. Raising power input from 52 to 72 HPD/ODT (horse power days per oven-dry ton) caused a loss of 27% in tensile index, and a loss in 20% burst. This is believed due to an increase in fines.

The development of pulp freeness, fiber length, brightness, tensile, tear, and burst were correlated with the percent of sodium sulfite used in the TMP process. Brightness and tear index were significantly affected at the level of 10% significance by the addition of sodium
sulfite. Sodium sulfite addition also reduced the shives content compared to TMP pulp. These results showed similar trends to those found in earlier studies (33) (37) (39) and (43) but differed in values because of freeness differences. This indicated that pretreatment using sodium sulfite under pressurized impregnation is also an effective sulfonation.

Pulp yield and opacity were negatively related with the percent of sodium sulfite. Addition of sodium sulfite resulted in loss of yield and opacity which were significant at the level of 10%. Overall the results showed the significant effect of sodium sulfite above 1% during TMP. Mokvist and Jackson (39) found similar loss of yield with addition of sodium sulfite during TMP.

Sodium sulfite pretreatment at 4% on the wood chips reduced the power requirement by 15% compared to no pretreatment.

Blow pulp pH was 7.1 for TMP and it was not affected by the addition of sodium sulfite liquor at different levels at pH 9. It was found in run 5 that the refiner power could be increased when the flat zone clearance was more than that of the conical zone. These results have not been reported in the previous studies.
CHAPTER VII

CONCLUSIONS

From the experimental results obtained in this study, the following conclusions can be made:

1. Pressurized impregnation of wood chips with sodium sulfite in a continuous process has shown improved pulp strength properties compared to earlier impregnation studies. This indicates that pressurized impregnation in the preheater (steam tube) is superior to room temperature or laboratory digester impregnation.

2. Increasing addition of sodium sulfite in the pressurized impregnation of wood chips before defibering showed trends similar to those found in earlier studies. Pulp unbleached brightness, tensile, tear, and burst increased while shive content, opacity, yield, and power requirements decreased.

3. The commercial viability of pressurized impregnation of wood chips with sodium sulfite in a continuous process is suggested by this study.

4. Water addition to the impregnator improved the development of TMP pulp physical properties.

5. The refiner power could be increased when the flat zone clearance was more than that of the conical zone.
6. Secondary refining improved pulp strength properties. The Mead refiner was effective as a secondary refiner in the laboratory to simulate the secondary refining process.

7. Blow pulp pH was not affected by the addition of sodium sulfite at the different levels.
CHAPTER VIII

SUGGESTIONS FOR FURTHER RESEARCH

The following topics for further study, related to the sulfonation of thermomechanical pulping to improve pulp properties without much loss of yield and opacity, have evolved during the course of this investigation:

1. This study should be repeated with other raw materials such as hardwoods and bagasse.

2. A study should be done to find the interactions between cooking time, cooking temperature, percentage of chemical, and pH of liquor and their effects on the development of pulp properties and fiber characteristics compared to TMP pulp.

3. This study should be repeated with different patterns of refiner plates to find the variation in the pulp properties and fiber length during TMP.

4. A study of the sulfonation of thermomechanical pulping should be done as inter-stage treatment (refiner addition) or post treatment.

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REFERENCES


Appendix A

General Description of Sunds Defibrator
General Description of Sunds Defibrator

Infeed Hopper

Infeed hopper, with metering screw. Built of stainless steel type M316 with a flanged inlet 12" x 30". The hopper is further provided with four 1/2" NPT steam inlets. The metering screw has a conical shaft and 4" flight diameter.

Technical Specifications:
Volume: Hopper 5 cu.ft.
Volume of the screw: 0.022 cu. ft./pitch
Speed of screw: 2 - 40 rpm

Screw Feeder

Screw feeder 4 PR, designed for feeding against steam pressure and liquor and all wetted parts of stainless steel type M316, bronze spilt wear sleeve. The screw feeder is equipped with plug pipes, feed screw, throat housing, bearing assembly, and further provided with a patented positive feeding arrangement. Cover plates with drain funnel surround the throat section. All equipment including screwfeeder bearing housing and drives is mounted on a steel hinged base. When the material is compressed into a plug, a pressure seal is formed between screwfeeder and preheater.
Technical Specifications:
volume of screw: 0.0085 cu. ft/pitch
speed of screw: 6 - 58 rpm

Preheater

The cooking time is regulated by the speed of the discharge screw.

Technical Specifications:
Working pressure max. 250 psi
Working temperature at 250 psi max. 406 F
Total Volume of Preheater 9.27 cu.ft.
Effective Volume (bottom of impregnator) 3.88 cu.ft.
Volume of Impregnator Screws 2 x 0.022 cu. ft./pitch
Volume of Impregnator 0.53 cu.ft.
Speed of Impregnator Screws 60HZ 18 rpm
Volume of Discharge Screw: 0.022 cu.ft./pitch
Blow back air cylinder 5" diameter - pressure min. 70 psi
Speed of discharge screw 1.5 - 25 rpm
Speed of agitator 60 HZ 4.5 rpm.

Defibrator 300 Feed Screw

Defibrator 300 feed screw, made from stainless steel type R316, a 4" diameter full flight screw with packing box. The feed screw housing is provided with a 3" vent line (steam return pipe) to the preheater for generated steam. The vent line has a 2" flanged connection for
steam relief valve.

Technical Specifications:

Volume of Screw: 0.022 cu. ft./pitch

Speed of Screw: 60 Hz 300 rpm.

**Defibrator 300 CD**

Type 300 CD, equipped with a "disc and cone" refining element. The two zones are adjustable independently from each other. The refining disc diameter is 12" + 4" cone (300 mm + 100 mm). The discs are encased in a stainless steel type K316 housing with split cover. The main body is also split horizontally for easy access and servicing. The housing is designed for a maximum operating pressure of 250 psi (1.7 MPa). The Defibrator 300 CD is provided with three flanged outlets (right-left-bottom). The side flange, left or right, is provided with a blow valve, by means of which the rate flow of the pulp is controlled. The bottom outlet is for atmospheric refining. The rotor is mounted on the main shaft by press fitting with an oil injection device.

The disc clearance for the inner zone (flat) is manually controlled by a hand wheel, and the disc clearance read on an indicator. One revolution of the handwheel = 0.2 mm movement of rotor. The disc clearance for the other zone (cone) is manually controlled by a handwheel on the stator. One revolution = 3 mm (0.12") axial movement = 0.78 mm (0.03") disc clearance. The CD

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zone is designed to permit addition of water and/or chemicals into the refining zone. The main shaft is equipped with a stainless steel hardfaced wear sleeve where the shaft goes through the packing box. The main shaft is supported by SKF type ball bearings.

Technical Specifications:
Refining disc diameter: 12" + 4" (300 mm + 100 mm)
Speed: Max 3600 rpm
Connected Power: Max. 200 hp
Working Pressure: Max. 250 psi.
Appendix B

Chip Classification
Figure 19. Diagram of Sunds Defibrator
SUNDS DEFIBRATOR
Single-stage TMP system with patented pressurized pulp cyclone.

Figure 20. Diagram of Pulp flow of Sunds Defibrator
Appendix B

Chip Classification
<table>
<thead>
<tr>
<th>Screen size</th>
<th>Percent weight of chips retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/8&quot; diameter</td>
<td>40.1</td>
</tr>
<tr>
<td>7/8&quot; diameter</td>
<td>17.4</td>
</tr>
<tr>
<td>5/8&quot; diameter</td>
<td>22.1</td>
</tr>
<tr>
<td>3/8&quot; diameter</td>
<td>16.6</td>
</tr>
<tr>
<td>3/16&quot; diameter</td>
<td>3.2</td>
</tr>
<tr>
<td>Residual catch pan</td>
<td>0.6</td>
</tr>
<tr>
<td>(bark, bast, dirt)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 21. Chip samples
Appendix C

Preparation and Strength Determination of Sodium Sulfite Solution (Liquor)
Preparation and Strength Determination of Sodium sulfite solution (liquor)

In each run of experiment, the sulfite content was determined as follows. As calculated amount of sodium sulfite was dissolved slowly to get required strength of solution. The solution was agitated thoroughly before titrating with Iodine solution. Next, the solution was titrated slowly with continuous stirring, with 0.1 n Iodine solution. The end point is the discharge at the Iodine color. Starch solution was used as an indictor.

Then, one milliliter 0.1 N Iodine = 0.003203 gr SO₂

The reaction taking place is
Na₂SO₃ + I₂ + H₂O = Na₂SO₄ + 2 HI

To determine the quantity of sulfur on sodium sulfite basis the following relation holds:

1 ml Iodine = 0.003203gr sulfur dioxide x (126.04gr sodium sulfite/64.06gr sulfur dioxide.

1 ml of Iodine = 0.006302gr of sodium sulfite

% of sodium sulfite = (gr of sodium sulfite/gr of solution weighed) x 100.
Appendix D

Standard Test Methods
Standard Test Methods

All physical tests performed on the pulps were made under the standard of the following TAPPI test methods:

<table>
<thead>
<tr>
<th>Test</th>
<th>TAPPI Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory Processing of Pulp</td>
<td>T-200 os-70</td>
</tr>
<tr>
<td>Forming of Handsheets</td>
<td>T-205 om-81</td>
</tr>
<tr>
<td>Physical Testing of Handsheets</td>
<td>T-220 om-83</td>
</tr>
<tr>
<td>Freeness of Pulp</td>
<td>T-227 om-58</td>
</tr>
<tr>
<td>Pulp Consistency</td>
<td>T-240 om-81</td>
</tr>
<tr>
<td>Laboratory Processing of Pulp (Plate Refiner method)</td>
<td>UM-221 om-81</td>
</tr>
<tr>
<td>Moisture Content of Wood Chips</td>
<td>T-258 os-76</td>
</tr>
<tr>
<td>Preparation of Mechanical Pulps</td>
<td>T-262 pm-81</td>
</tr>
<tr>
<td>PH of Paper Extracts</td>
<td>T-509 su-68</td>
</tr>
<tr>
<td>Preparation and Standardization of Volumetric Solutions</td>
<td>T-610 n-60</td>
</tr>
<tr>
<td>Sulfur Dioxide in Sulfite Cooking Liquor</td>
<td>T-604 su-70</td>
</tr>
</tbody>
</table>
Appendix E
Sample Calculations
Sample Calculations

1. Pulp Yield Determination:

For TMP Yield, \%
\[= \left(\frac{X \times A}{Y(100-B)}\right) \times 100\]

Pulp production rate (X) = 1.02195 Kgs/min
Blow pulp consistency (A) = 59.2%
Chips feed rate (Y) = 0.9539 Kgs/min
Chips moisture (B) = 33%

Calculation:
\[\text{TMP Yield} = \left(\frac{1.02195 \times 0.592}{0.9539(100-33)}\right) \times 100\]
= 94.66%

For CTMP Yield, \%
\[= \left(\frac{X \times A}{Y(100-B)} + S\right) \times 100\]
4% Sodium sulfite addition rate (S) = 0.02556 Kgs/min

Calculation:
\[\text{CTMP Yield} = \left(\frac{1.02195 \times 0.592}{0.9539(100-33)} + 0.02556\right) \times 100\]
= 91.20%

2. Power Consumption:

Power Consumption (HPD/ODT) = \left(\frac{P \times 200}{100}\right) - 20 \ T
Percentage of power applied (P) = 45
Production rate (T) = 0.871 ODT/Day

Calculation:
\[\text{Power Consumption} = \left(\frac{45 \times 200}{100}\right) - 20 \times 0.871\]
= 61 HPD/ODT
Appendix F

Defibrator Operating Parameters
## Defibrator Operating Parameters

### Table 18

**Run 1 Defibrator Operating Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed Hopper</td>
<td>Presteam for 10 min.</td>
</tr>
<tr>
<td>Hopper Plug Screw Feed</td>
<td>Crush chips at 30 psi</td>
</tr>
<tr>
<td>Impregnator</td>
<td>No water added</td>
</tr>
<tr>
<td>Preheater</td>
<td>12 min. at 35 psi</td>
</tr>
<tr>
<td>Refiner Load</td>
<td>28.5 HPD/ODT</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.85 to 0.90 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.60 to 0.65 mm</td>
</tr>
<tr>
<td>Through-put</td>
<td>659.36 g/min.</td>
</tr>
</tbody>
</table>

**Defribator dilution water flows:**

- Primary infeed dilution flow: 0.30 Cpm
- CD dilution flow: 0.28 Cpm
- Chips moisture: 32%
- Blow pulp consistency: 33 to 40%
- Sodium Sulfite, %: 0, 4
Table 19

Run 2 Defibrator Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed Hopper</td>
<td>Presteam for 10 min.</td>
</tr>
<tr>
<td>Hopper plug screw Feed</td>
<td>Crush chips at 25 psi</td>
</tr>
<tr>
<td>Impregnator</td>
<td>Without/With water at 275 psi (10% to the pulp flow)</td>
</tr>
<tr>
<td>Preheater</td>
<td>10 to 12 min. at 30 psi</td>
</tr>
<tr>
<td>Refiner load</td>
<td>52.00 HPD/ODT</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.6 to 0.7 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.4 to 0.45 mm</td>
</tr>
<tr>
<td>Through-put</td>
<td>598 g/min.</td>
</tr>
<tr>
<td>Defibrator dilution water flows:</td>
<td></td>
</tr>
<tr>
<td>Primary infeed dilution flow</td>
<td>0.21 Cpm</td>
</tr>
<tr>
<td>CD dilution</td>
<td>0.15 Cpm</td>
</tr>
<tr>
<td>Chips moisture</td>
<td>32 to 34%</td>
</tr>
<tr>
<td>Blow pulp consistency</td>
<td>50 to 56%</td>
</tr>
<tr>
<td>Sodium Sulfite, %</td>
<td>0, 4</td>
</tr>
</tbody>
</table>
Table 20

Run 3 Defibrator Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed Hopper</td>
<td>Presteam for 10 min.</td>
</tr>
<tr>
<td>Hopper plug screw Feed</td>
<td>Crush chips at 25 psi</td>
</tr>
<tr>
<td>Impregnator</td>
<td>With water at 275 psi (10% to the pulp flow)</td>
</tr>
<tr>
<td>Digester</td>
<td>10 at 30 psi</td>
</tr>
<tr>
<td>Refiner load</td>
<td>75 HPD/ODT</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.45 to 0.50 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.25 to 0.30 mm</td>
</tr>
<tr>
<td>Through-put</td>
<td>575 g/min.</td>
</tr>
<tr>
<td>Defibrator dilution water flows:</td>
<td></td>
</tr>
<tr>
<td>Primary infeed dilution flow</td>
<td>0.24 Cpm</td>
</tr>
<tr>
<td>CD dilution</td>
<td>0.18 Cpm</td>
</tr>
<tr>
<td>Chips moisture</td>
<td>33 to 33.6%</td>
</tr>
<tr>
<td>Blow pulp consistency</td>
<td>55%</td>
</tr>
<tr>
<td>Sodium Sulfite, %</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 21

Run 4 Defibrator Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed Hopper</td>
<td>Presteam for 10 min.</td>
</tr>
<tr>
<td>Hopper plug screw</td>
<td>Crush chips at 25 psi</td>
</tr>
<tr>
<td>Feed Impregnator</td>
<td>With water at 275 psi (10% to the pulp flow)</td>
</tr>
<tr>
<td>Preheater</td>
<td>10 min. at 30 psi</td>
</tr>
<tr>
<td>Refiner load</td>
<td>53 to 61 HPD/ODT</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.50 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.25 mm</td>
</tr>
<tr>
<td>Through-put</td>
<td>605 g/m.</td>
</tr>
<tr>
<td>Defibrator dilution</td>
<td></td>
</tr>
<tr>
<td>water flows:</td>
<td></td>
</tr>
<tr>
<td>Primary infeed dilution flow</td>
<td>0.19 Cpm</td>
</tr>
<tr>
<td>CD dilution</td>
<td>0.22 Cpm</td>
</tr>
<tr>
<td>Chips moisture</td>
<td>33 to 34%</td>
</tr>
<tr>
<td>Blow pulp consistency</td>
<td>56 to 64%</td>
</tr>
<tr>
<td>Sodium Sulfite, %</td>
<td>0, 2, 4</td>
</tr>
</tbody>
</table>
Table 22
Run 5 Defibrator Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infeed Hopper</td>
<td>Presteam for 10 min.</td>
</tr>
<tr>
<td>Hopper plug screw Feed</td>
<td>Crush chips at 25 psi</td>
</tr>
<tr>
<td>Impregnator</td>
<td>With water at 275 psi (10% to the pulp flow)</td>
</tr>
<tr>
<td>Preheater</td>
<td>10 to 12 min. at 30 psi</td>
</tr>
<tr>
<td>Refiner load</td>
<td>Not taking load</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.25 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.35</td>
</tr>
<tr>
<td>Through-put</td>
<td>No good pulp</td>
</tr>
</tbody>
</table>

Defibrator dilution water flows:
- Primary infeed dilution flow: 0.19 to 0.28 Gpm
- CD dilution: 0.15 to 0.26 Gpm
- Chips moisture: 32 to 34%
- Sodium Sulfite, %: 0
### Table 23

#### Run 6 Defibrator Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hopper plug screw Feed</td>
<td>Crush chips at 25 psi</td>
</tr>
<tr>
<td>Impregnator</td>
<td>With water at 275 psi (10% to the pulp flow)</td>
</tr>
<tr>
<td>Preheater</td>
<td>10 min. at 30 psi</td>
</tr>
<tr>
<td>Refiner load</td>
<td>53 to 62 HPD/ODT</td>
</tr>
<tr>
<td>Plate Clearance</td>
<td>Disk...0.40 to 0.45 mm</td>
</tr>
<tr>
<td></td>
<td>Conical...0.25 to 0.30 mm</td>
</tr>
<tr>
<td>Through-put</td>
<td>610 g/min.</td>
</tr>
</tbody>
</table>

**Defibrator dilution water flows:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary infeed dilution flow</td>
<td>0.22 Cpm</td>
</tr>
<tr>
<td>CD dilution</td>
<td>0.19 Cpm</td>
</tr>
<tr>
<td>Chips moisture</td>
<td>33 to 34%</td>
</tr>
<tr>
<td>Blow pulp consistency</td>
<td>45 to 50%</td>
</tr>
<tr>
<td>Sodium Sulfite, %</td>
<td>0, 1, 2</td>
</tr>
</tbody>
</table>
Appendix G
Regression Equations
Regression Equations

Run 4

\( X = \text{percent of sodium sulfite} \ 0, \ 2, \ 4 \)

\begin{align*}
\text{Freeness} & \quad Y = 357.333 + 22.5 \ X \\
\text{Fiberlength} & \quad Y = 1.5625 + 0.02625 \ X \\
\text{Yield} & \quad Y = 94.786 - 0.58 \ X \\
\text{Shives} & \quad Y = 3.4266 - 0.195 \ X \\
\text{Brightness} & \quad Y = 35.125 + 1.552 \ X \\
\text{Opacity} & \quad Y = 96.933 - 0.6 \ X \\
\text{Tensile} & \quad Y = 6.133 + 0.85 \ X \\
\text{Tear} & \quad Y = 2.483 + 0.465 \ X \\
\text{Density} & \quad Y = 0.3166 + 0.00302 \ X \\
\end{align*}

Run 6

\( X = \text{Percent of sodium sulfite} \ 0, \ 1, \ 2 \)

\begin{align*}
\text{Freeness} & \quad Y = 206 + 20 \ X \\
\text{Fiberlength} & \quad Y = 1.5983 + 0.045 \ X \\
\text{Yield} & \quad Y = 95.616 - 0.45 \ X \\
\text{Shives} & \quad Y = 4.0916 - 0.175 \ X \\
\text{Brightness} & \quad Y = 34 + 0.9 \ X \\
\text{Opacity} & \quad Y = 96.683 - 0.65 \ X \\
\text{Tensile} & \quad Y = 7.633 + 0.90 \ X \\
\text{Tear} & \quad Y = 2.766 + 0.5 \ X \\
\text{Density} & \quad Y = 0.3247 + 0.00525 \ X \\
\text{Burst} & \quad Y = 0.3241 + 0.0125 \ X \\
\text{Blow pH} & \quad Y = 7.033 + 0 \ X \\
\end{align*}
Appendix H

Kajaani Fiber Length Distribution
Analysis of Fiber Length for TMP (0% Sodium Sulfite)

By Kajaani FS-100 Analyzer

<table>
<thead>
<tr>
<th>Sample</th>
<th>TMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1114</td>
</tr>
<tr>
<td>0.20</td>
<td>1780</td>
</tr>
<tr>
<td>0.41</td>
<td>979</td>
</tr>
<tr>
<td>0.61</td>
<td>541</td>
</tr>
<tr>
<td>0.82</td>
<td>276</td>
</tr>
<tr>
<td>1.02</td>
<td>167</td>
</tr>
<tr>
<td>1.23</td>
<td>99</td>
</tr>
<tr>
<td>1.44</td>
<td>61</td>
</tr>
<tr>
<td>1.64</td>
<td>52</td>
</tr>
<tr>
<td>1.85</td>
<td>28</td>
</tr>
<tr>
<td>2.05</td>
<td>22</td>
</tr>
<tr>
<td>2.26</td>
<td>18</td>
</tr>
<tr>
<td>2.67</td>
<td>23</td>
</tr>
<tr>
<td>3.08</td>
<td>13</td>
</tr>
<tr>
<td>3.50</td>
<td>5</td>
</tr>
<tr>
<td>3.91</td>
<td>2</td>
</tr>
<tr>
<td>4.32</td>
<td>2</td>
</tr>
<tr>
<td>4.73</td>
<td>0</td>
</tr>
<tr>
<td>5.14</td>
<td>0</td>
</tr>
<tr>
<td>5.55</td>
<td>0</td>
</tr>
<tr>
<td>5.97</td>
<td>0</td>
</tr>
<tr>
<td>6.38</td>
<td>0</td>
</tr>
<tr>
<td>6.79</td>
<td>0</td>
</tr>
<tr>
<td>&gt;</td>
<td>0</td>
</tr>
</tbody>
</table>

Characteristics
Total Fibers  5183

<table>
<thead>
<tr>
<th>Char</th>
<th>Weighted</th>
<th>Arithmetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>Q1</td>
<td>0.36</td>
<td>0.02</td>
</tr>
<tr>
<td>Q2</td>
<td>0.70</td>
<td>0.18</td>
</tr>
<tr>
<td>Q3</td>
<td>1.24</td>
<td>0.44</td>
</tr>
<tr>
<td>D9</td>
<td>2.03</td>
<td>0.83</td>
</tr>
<tr>
<td>Av</td>
<td>0.83</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Analyzed by Kajaani FS-100
Analysis of Fiber Length for CTMP2 (2% Sodium Sulfite)

By Kajaani FS-100 Analyzer

<table>
<thead>
<tr>
<th>Sample</th>
<th>CTMP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1156</td>
</tr>
<tr>
<td>0.20</td>
<td>1727</td>
</tr>
<tr>
<td>0.41</td>
<td>881</td>
</tr>
<tr>
<td>0.61</td>
<td>445</td>
</tr>
<tr>
<td>0.82</td>
<td>236</td>
</tr>
<tr>
<td>1.02</td>
<td>182</td>
</tr>
<tr>
<td>1.23</td>
<td>105</td>
</tr>
<tr>
<td>1.44</td>
<td>85</td>
</tr>
<tr>
<td>1.64</td>
<td>66</td>
</tr>
<tr>
<td>1.85</td>
<td>38</td>
</tr>
<tr>
<td>2.05</td>
<td>27</td>
</tr>
<tr>
<td>2.26</td>
<td>22</td>
</tr>
<tr>
<td>2.67</td>
<td>26</td>
</tr>
<tr>
<td>3.08</td>
<td>5</td>
</tr>
<tr>
<td>3.50</td>
<td>3</td>
</tr>
<tr>
<td>3.91</td>
<td>1</td>
</tr>
<tr>
<td>4.32</td>
<td>0</td>
</tr>
<tr>
<td>4.73</td>
<td>3</td>
</tr>
<tr>
<td>5.14</td>
<td>0</td>
</tr>
<tr>
<td>5.55</td>
<td>0</td>
</tr>
<tr>
<td>5.97</td>
<td>0</td>
</tr>
<tr>
<td>6.38</td>
<td>0</td>
</tr>
<tr>
<td>6.79</td>
<td>0</td>
</tr>
</tbody>
</table>

---

Characteristics

<table>
<thead>
<tr>
<th>Weighted</th>
<th>Arithmetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.17</td>
</tr>
<tr>
<td>Q1</td>
<td>0.38</td>
</tr>
<tr>
<td>Q2</td>
<td>0.77</td>
</tr>
<tr>
<td>Q3</td>
<td>1.38</td>
</tr>
<tr>
<td>D9</td>
<td>2.03</td>
</tr>
<tr>
<td>Av</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5009

Analyzed by Kajaani FS-100

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Analysis of Fiber Length for CTMP4 (4% Sodium Sulfite)

By Kajaani FS-100 Analyzer

Sample CTMP4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>808</td>
</tr>
<tr>
<td>0.20</td>
<td>1368</td>
</tr>
<tr>
<td>0.41</td>
<td>901</td>
</tr>
<tr>
<td>0.61</td>
<td>553</td>
</tr>
<tr>
<td>0.82</td>
<td>393</td>
</tr>
<tr>
<td>1.02</td>
<td>275</td>
</tr>
<tr>
<td>1.23</td>
<td>197</td>
</tr>
<tr>
<td>1.44</td>
<td>149</td>
</tr>
<tr>
<td>1.64</td>
<td>92</td>
</tr>
<tr>
<td>1.85</td>
<td>104</td>
</tr>
<tr>
<td>2.05</td>
<td>60</td>
</tr>
<tr>
<td>2.26</td>
<td>45</td>
</tr>
<tr>
<td>2.67</td>
<td>56</td>
</tr>
<tr>
<td>3.08</td>
<td>25</td>
</tr>
<tr>
<td>3.50</td>
<td>6</td>
</tr>
<tr>
<td>3.91</td>
<td>3</td>
</tr>
<tr>
<td>4.32</td>
<td>0</td>
</tr>
<tr>
<td>4.73</td>
<td>0</td>
</tr>
<tr>
<td>5.14</td>
<td>0</td>
</tr>
<tr>
<td>5.55</td>
<td>0</td>
</tr>
<tr>
<td>5.97</td>
<td>0</td>
</tr>
<tr>
<td>6.38</td>
<td>0</td>
</tr>
<tr>
<td>6.79</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Characteristics

Total Fibers 5035

<table>
<thead>
<tr>
<th>Char</th>
<th>Weighted</th>
<th>Arithmetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.28</td>
<td>0.00</td>
</tr>
<tr>
<td>Q1</td>
<td>0.55</td>
<td>0.07</td>
</tr>
<tr>
<td>Q2</td>
<td>1.02</td>
<td>0.29</td>
</tr>
<tr>
<td>Q3</td>
<td>1.66</td>
<td>0.71</td>
</tr>
<tr>
<td>D9</td>
<td>2.28</td>
<td>1.30</td>
</tr>
<tr>
<td>Av</td>
<td>1.17</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Analyzed by Kajaani FS-100

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Figure 22. Comparison of Fiber Length Distribution

Comparison of Fiber Length Distribution

Number of Fibers

Fiber Length, mm

CTMP

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BIBLIOGRAPHY


Creighton, T. J., "Thermomechanical Pulping." Sprout-Bauer Company, Current Topics Class Notes, Western Michigan University, October 1, 1986.


