The Effects of Fines, Drying Intensity and Recycling on Pulp and Paper Properties

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THE EFFECTS OF FINES, DRYING INTENSITY AND RECYCLING ON PULP AND PAPER PROPERTIES

by

Chiranjiv K. Singh

A Thesis
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Chiranjiv K. Singh
THE EFFECTS OF FINES, DRYING INTENSITY AND RECYCLING
ON PULP AND PAPER PROPERTIES

Chiranjiv K. Singh, M.S.
Western Michigan University, 1996

The effects of fines level, drying intensity and recycling on pulp and paper properties of bleached softwood kraft were evaluated graphically and statistically.

Fiber fines (100-mesh) were mixed in proportions of 0, 10, 20, 40% with the long fiber fraction. These pulps were tested for fiber length distribution. Handsheets prepared from these pulps were dried at low (air dry) and high (220°F, 4.25 min) drying intensities. These handsheets were recycled and new handsheets were dried at the above drying levels.

Water retention values increased with increasing level of fines for virgin pulp. Recycling resulted in a 20% decrease in water retention values as compared to never dried fibers. Tensile, wet web strength and density increased, while scattering coefficient and tear decreased with fines addition for both virgin and recycled paper.

Results were analyzed considering variables 'fines addition', 'recycling' and 'drying intensity' in the $2^3$ factorial statistical model. Fines addition' and 'recycling' were significant in affecting scattering coefficient and tensile strength, while tear was significantly affected by fines addition at 95% confidence level.

High intensity drying resulted in higher scattering coefficient, lower density and lower tensile than the low intensity drying, suggesting reduced bonding due to high rate of drying and/or "overdrying".
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CHAPTER I

INTRODUCTION

Considerable research has been done on the effects of fines on paper properties. The often inconsistent effects of fines on paper strength and optical properties arise from dependence of fiber and fines characteristics on many factors. The comparison between the results from the various studies cannot be made unless the studies are directed in the same manner using the same wood species, pulping and bleaching methods, refining and papermaking techniques. In addition, study of the effects of recycling on the various pulp and paper properties is mostly directed towards the often desirable, long fiber constituents of the paper. It has been established that the various strength and optical properties of the paper go through some changes during recycling. Drying processes involved in the recycling are often considered as the main variables affecting the properties of fiber constituents of paper. Although various studies (1,2,3) have been published on the effects of drying on pulp and paper, some discrepancies exist regarding the behavior of fines as affected by recycling.

In this project, hand prepared sheets with different proportions of fines were recycled. Paper sheets were dried at different drying intensities to evaluate their effects on wet web strength, water retention values, freeness and some of the paper properties.
CHAPTER II

LITERATURE ANALYSIS

Fines and Paper Properties

Papernaking fines are often characterized as primary and secondary. Primary fines are present in the original wood species and are found in the unrefined pulp, following pulping. These fines consist of parenchyma cells, vessel segments, film-like fragments derived from middle lamella or outer cell wall layers and amorphous particles of mineral and chemical origin (4). Through SEM analyses, Hawes and Doshi (5) found that primary fines were made up of flake-like, chunky particles. Due to their low surface area, primary fines did not contribute much to bonding strength. In addition, the primary fines were found to be stiffer and less conformable than secondary fines. Secondary fibers were produced during refining and result from the partial removal of primary and secondary walls of the fibers (5). Many studies (5-10) have found that the high surface area of these fibrillar secondary fines was the reason for their better bonding abilities.

Reif (11) found significant increases in burst, breaking length, fold and density and decrease in the tear strength, with the addition of fines. This effect was correlated with the effect of beating. He concluded that beating and addition of fines to unbeaten chemical pulp similarly influenced the inter-fiber bonding properties of the paper. He proposed that the degree of surface area development of pulp was the prime criterion for the production of
inter-fiber bonding, rather than the methods used to achieve this development.

Gartshore (12) showed that fines from refined unbleached sulfate pulps could contribute considerably to paper strength. High intensity refining led to fiber cutting, while low intensity refining favored fiber development and generation of fibrillar fines.

Richardson (13) classified the fines into >100 microns, 85-100 microns, 60-85 microns and 20-60 microns fractions. These fines were added to the unclassified pulp. Sheets with fines of smaller size resulted in higher burst and tensile strength. Richardson stated that strength improvement with the addition of fines, was sufficient gain, even at the expense of loss of drainage, with the exception of fines smaller than 20 microns.

Miller, Peterson and Shankar (14) found increases in sheet density and tensile strength as the fines became smaller in the case of CTMP (treated with 7% NaOH).

Mohlin (7) reported increases in tensile, initial wet web strength and Scott bond strength with increasing level of fines. He concluded that the size of the fines fraction was the determining factor in the development of strength properties. Mohlin (7) stated that white water should be re-circulated during formation to ensure comparable retention of fines in each sheet. Marton (8) found great differences in the surface activity of fines and fillers which lead to higher adsorption of alum and other additives on fines than that on fibers per unit mass.

Springer and Pires (14) found in case of Northern softwood kraft and CTMP fines, (tissue grade) that due to their greater surface area, fines were able to form more interfiber bonds as measured by short span tensile tests. Based on the results they stated that a small
amount of fines caused a great increase in the number of bond sites. They confirmed that the fines were more important in increasing tensile strength than long-fiber portion of the sheet. Later (15) they found that fines had a positive effect on wet web tensile strength of paper.

Fines and Swelling

Corson (16) found that pulp fines swell considerably and retained two to three times as much water as the coarser fibers. The high swelling enabled the fines to conform better to the network structure and to even out stress concentrations in the dried paper, resulting in a more uniform and stronger sheet.

Giertz (17) found that sheet densities decreased as the fines were removed from refined bleached sulfite and sulfate pulps. Higher density of corresponded to better bonding in the sheet. Tensile strength, stiffness and elongation were higher, while light scattering was lower for the sheets made out of all the fines containing pulps. Giertz attributed the increased bonding due to stronger Campbell forces, due to the presence of fines. He determined values for bound water by centrifugation and solute exclusion and found that fibrils and fines contained extra amounts of bound water, presumed to be in the swollen hemicellulose. It was proposed that in the wet web, these fibril/water/fines formed a strong wet bonding between fiber networks. During drying, the system shrunk as a glutinous gel, pulling the fibers together resulting in fiber-fiber bonds in the dry sheet.
Thode and Ingman (6) showed that the external surface area of pulp fibers and fines increased with swelling. They proposed that the major role of surface development and fines in producing strength was to provide greater surface tension forces (Campbell's effect). Due to this effect the fibers are drawn together for bond formation as water is removed. They further stated that for a given total bonded area, the strength of the paper should be independent of the surface area of fibers or the concentration of the fines present (6). But it is apparent that total bonded area also depends on the total surface area which definitely increases with the addition of the fines. So it can be proposed that the higher surface area of fines could be one of the contributing factors towards the strength development. High swelling of the fines raised the surface area of the fines, leading to more contacts between the bonding sites and thus better bonding.

According to Stone and Scallan (18), refined Kraft lost 30% of its swelling ability after drying. The above authors (18) and Lundberg and de Ruvo (1) attributed the decrease in swelling to irreversible closure of large pores and healing of the cracks in the cell wall during drying. They also suggested that strain hardening takes place during drying which could be reflected in characteristic changes in the elastic and flow properties of the dried sheet. It was proposed (1,18) that increased hydrogen bonding during drying also promotes the healing of cracks and thus once dried fibers will have less tendency to delaminate during beating than the virgin fibers.
Fines and Water Retention Values

Zhao et al (19) examined the effect of beating on water retention values of wheat straw pulps. They found that beating substantially increased the water retention value of wheat straw pulp. The water retention value (WRV) of fiber fraction of pulp showed little increase, because the fiber surface did not undergo external fibrillation. In this case, the increase in the WRV of the whole pulp was attributed to an increase in the amount of fines during beating.

Jayme (9) confirmed that increased addition of fibrillar fines to pulp increased tensile, burst and sheet density, while it decreased the tear. He found a straight line relationship between water retention values and breaking length developed during the refining process.

Iwamida, Sumi and Nakamo (20) related water retention values (WRV) of the pulps (neutral sulfite, bisulfite and acid sulfite) with the resulting paper properties. Primary fines and secondary fines were treated individually and added to the pulps. The study showed that WRVs for fines were much higher than those for the long fibers. They attributed high water retention values to high degree of swelling of the fines. Marton (8) also indicated higher swelling ability of fines as compared to that of fibers.

Ingman and Andrews (21) found a correlation of filtration resistance to the amounts of fines present and attributed this phenomenon to the high surface area of fines as compared to that of fibers. High water retention values of fines affected the rate of drainage
in terms of decreasing the drainage rate as the fines level increased. Reif (11) suggested that fines in a pulp obstruct the pores in a forming web, decreasing the relative size of the channels through which water must flow, causing a decrease in the drainage rate.

Fines and Light Scattering

Using pressurized ground wood (PGW), thermomechanical pulp (TMP), stonegroundwood (SGW), for his study, Lindholm (22) found increases in density, Scott bond strength and decrease in drainage, while tear first increased and then decreased with the increasing levels of fines in the pulp. Light scattering was found out to be highest for the least refined fines. This property also decreased with decreasing freeness.

Hawes and Doshi (5) found that unbleached kraft or recycled pulp fines (-200 mesh) whether primary or secondary, when added to unrefined recycled kraft pulp, significantly increased the sheet density, tensile strength, burst strength, tear and fold. Addition of fines to the recycled pulp resulted in decrease in the air permeability of the sheet (5). Addition of fines did not significantly affect scattering coefficient. This indicated that kraft fines were bonded to the fibers giving no extra area for light scattering. Through SEM analysis, Hawes and Doshi (1) observed that secondary fines were film like, adhering well to the fiber surface. The visual observation was in agreement with the fact that tensile strength increased with the increasing water retention values. It was hypothesized that due to higher water retention values of the pulp with the fines, that hydrogen bonding improved. In the case of TMP, fines increased the scattering coefficient, while strength
properties were unaffected. Higher compressibility of kraft fines than that of TMP, facilitated closer fiber contact and thus improved bonding. Lidholm (22), also found that for TMP, light scattering increased with fines addition. This indicated that for these two studies (5,22), TMP fines did not bond well to the fibers leading to an increase in the scattering coefficient. Through chemical analysis, secondary fines of TMP were found to have higher hemicellulose level than primary fines, while hemicellulose level for chemical pulp fines was higher for primary than that for secondary. It appears that for strength development, the chemical nature of fines is not as important as higher surface area and higher swelling and water holding capacity of the fines. As Marton (8) explained, high swelling ability of fines allows them to conform better to the fiber/fines network.

Corson (16) studied the influence of fibers and fines on wet and dry properties of thermomechanical pulps. He found that if fiber was refined sufficiently to develop its inherent properties, there was sufficient fine material available to consolidate it into a dense network with good wet web and dry strength properties. The results showed that wet web tensile index, elongation, dry sheet density, tensile and scattering coefficient increased with the increase in fines content in a sheet only to a certain level. At very high levels of fines (above 40%) in the pulp, tensile and elongation decreased. He stated that the optical properties in the form of light scattering could be further enhanced by replacing the short fiber material by fines, but this effect could be achieved only at the expense of sheet strength. This study (16) confirms that the findings of authors of (5,22), that for TMP, light scattering increased with fines addition.
In a study involving groundwood and sulfite fines, Langin (23) found that fines reached a maximum wet tensile when stock consisted of approximately 50% by weight of fines. The contribution of fines to wet web tensile strength, indicated that fines not only contributed to bonding but also played a role in forming a kind of consolidated bridging network, which resulted in better wet web strength (16,23).

Lobben (24) studied the relative contribution of fibers and fines fraction of pulp on the shrinkage and elongation of paper sheets. He found that elongation values were more sensitive to the fines component in the pulp. He believed that the major effect of fines in unbeaten fiber sheets was the reduction of local stress concentrations in the bonded fiber crossings, which allowed a more uniform stress distribution during tensile loading.

Effects of Drying

Yamuchi and Kibblewhite (25) in a study involving mercury porosimetry and SEM of radiata pine, found that air drying of wet pressed webs caused consolidation to increase over that achieved by pressing, primarily through the development of surface tension forces between fibers, fiber fragments, and fines present in the TMP furnish (25).

Recycling causes an effect, called “hornification” by McKee (26). He proposed that the drying process results in stiffening of the fiber, decreasing its ability to conform.

Avert and Weston (27) attributed the weakness of recycled paper to the loss of bond strength and/or area of bonds and not to the loss in fiber tensile strength. They further stated that loss of wet fiber plasticity and conformability caused in the drying process can
be overcome by pressing. They found that light scattering decreased with increased pressing. Because the recycled fibers are bulky and stiff, increased pressing could allow the fibers to come close to each other and achieve the same density as that of never-dried pulp. It can be reasoned that the ability of the pressing process to increase the strength of paper is limited and this benefit of increased density cannot be fully exploited in recycled paper.

Schwarcsztajn et al. (28) found that drying reduced the fiber bonding potential and fiber specific surface area. Drying leads to irreversible reduction in the swelling ability of cellulose. This was interpreted as being the result of the formation of new junction zones between microfibrils by means of trains of hydrogen bonds, which were stable towards rewetting because of their cooperative bonding effects (28).

The moisture content at which hornification starts during drying was believed to be closely related to the extent of cell wall swelling before drying (29). For more swollen pulp, irreversible shrinkage started at a higher moisture content. The degree of so called hornification (26,28) then gradually increased with solids content until complete dryness was reached (29).

Lundgerg and Ruvo (1) studied the mechanical properties of sheets made from bleached kraft fibers, previously dried freely or under restraint at various temperatures and reslushed and recycled. The application of restraint during drying resulted in somewhat lower swelling than that for the fibers obtained from freely dried sheet. It was suggested that hindrance to swelling on rewetting was influenced by deformations in the cell wall during drying. They found that the water retention values of paper sheets dried at higher
temperatures (248°F) were lower than those dried at lower temperatures (68°F) for the same virgin pulp (1). The water retention values for beaten and once-dried fibers were found to be the same as that of unbeaten never-dried pulp. Thus, the swelling gained in the beating of fibers was lost as a result of drying, even at low temperatures. Higher drying temperatures reduced the degree of swelling, but this effect was found out to be smaller than that of drying alone. The results were in agreement with those of Scallan (18) that subsequent beating restored the swelling ability of fibers dried at lower temperatures. After drying at higher temperatures it was not possible to restore the swelling to the original value, even after prolonged beating (1,18). This indicated that the development of swelling restrictions was made permanent by the establishment of irreversible bonding and hornification in the cell wall when high temperature drying was performed.

The structure and strength behavior of the paper were thought to be largely dependent on the events occurring during the removal of the last fraction of water during drying (28,29). The development of the sheet structure during drying was accompanied by measurable changes in the mechanical properties of the web and these changes provide an understanding of the behavior exhibited by a sheet of paper (28,29).

Drying was visualized as a process where the rectangular microfibrils associate laterally to form sheets by the formation of tangential bonds between the microfibrils (18). The degree of cell wall collapse on drying was believed to be generally higher for beaten fibers than for unbeaten fibers, because larger pores are preferentially created during
beating (30). Many authors suggested that larger pores close during a drying and rewetting cycle (2, 18, 29, 31).

Internal Stress

The magnitude of the internal stress in handsheets made from bleached kraft pulp was found to increase with the increase in the restraint applied during drying (32). According to Htun et al. (32), internal stresses may arise at different structural levels, between fiber/fines flocs, between fibers, or between microfibrils and matrix within the fiber. At the ultrastructural level, internal stresses were related to deformations of kinks and disordered zones associated with local stress fields in the structure (32). Internal stresses were supposed to develop in the sheet during the course of drying mainly because of the inevitable in-plane tension forces, but also because of a nonuniform drying rate in the thickness direction (32).

According to Robertson et al. (33), high internal stress could be built into a stiff cell wall matrix in which viscous flow during drying is limited. These stresses may be released during rewetting provided the cell wall swells again. If the stresses are allowed to relax, by increasing the time or temperature of drying, the degree of irreversible cell wall collapse increases (33). According to Lindstrom (29) restraint drying of well beaten fibers in the sheets give a high internal stress (23).

The work of Johnson and Kubak (34) and Craven (35) showed that the level of internal stress increases with the increasing tension applied to the web during drying. These
authors believed that internal stress might be related to the drying stress. The various changes which lead to higher internal stress also lead to higher drying stress. The development of drying forces had been variously explained in the literature as Campbell forces, hydrogen bonding, stress distributions in the fiber network, and macroscopic structural changes in the fibers and the sheet (28).

Byrd (36) calculated a fiber bonding index from the final drying force and the total web shrinkage observed during drying. Htun et al. (37) found that for the various sheets made from a bleached kraft pulp the internal stress was essentially equal to final drying stress (37). The relationship between the internal stress and drying stress did not change in any significant manner with the degree of bonding, the level of wet pressing, or the utilization of different fiber fractions in the sheet (37). The mechanical properties of paper dried under restraint correlated well with the final drying stress, irrespective of the type of the pulp, degree of beating, wet-pressing level, or use of different fiber fractions (38). The close relationship between the mechanical properties and drying stress is important since it means that the mechanical properties of paper may be predicted and controlled by measuring and controlling the web tension in the dryer section of the paper machine (32,38).

A greater degree of restraint during drying leads not only to lower strain to failure (39), but higher elastic modulus of the final sheet (40,41). Van den Akker (42) suggested that the increase in tensile strength caused by drying under tension is due to the equalization of the distribution of stress among the fibers. He proposed that when the
moisture content was high, the fibers and fiber-fiber bonds were in plastic state and could easily undergo straightening and alignment. This condition could have become frozen in when the paper was dried so that the fibrous elements were in a position to take up the load more equally (41,42).

Craven (43) postulated that since it is the Campbell effect that pulls surfaces closer to each other for bonding to be established, the application of tension during drying postpones the onset of bonding so that the final bonds are formed over a narrower drying range. These bonds would then be under more uniform state of initial stress during subsequent loading, than if shrinkage was allowed during drying (41,43).

Giertz (44) postulated that when paper was dried under restraint, the free fiber segments were straightened due to microcompressions taking place at fiber crossings and these segments were active in taking up load. It seems possible that the role of the fines would be important at these fiber crossings leading to more uniform stress transfer.

Ellis and Sadlachek (45) attributed reduced bonding to stiffening and hardening of the fiber. The intrinsic fiber strength of the fiber was not believed to deteriorate through recycling, however it decreased sometimes. It was suggested that the loss of fiber flexibility and plasticity is due to reduced swelling capacity of the fiber once it has been dried (45).

Ruvo et al. (2) found that acetylated fiber retained its reswelling ability and thus the properties were recovered to higher extent after drying. It was believed that acetylation of virgin pulp leaves a hydrophobic lining on the surfaces of large pores. These acetylated
pores were permanent and were not responsive to the effects of “hornification” and were not healed by drying (2).

Recycling and Fines

Ruvo et al (1) found that for the whole unclassified pulp (with fines), both drying and increased drying temperature reduce the swelling of the long fibers. They further stated that tendency to produce fines during drying, repulping, and beating increased with the temperature of drying. Fines obtained in the beating to a large extent consisted of microfibrils, which were strongly coupled to each other by the bonding mechanism that took place during drying (5). Thus when liberated after drying, they did not have the same ability to reswell as fines from virgin fibers. They contribute more to the specific surface area of the suspension than to the swelling potential. Therefore these fines had little effect on strength and more on drainage properties (1).

Schuelke (46) studied the effect of drying on fines-free and unclassified kraft pulp. Three levels of drying were used; air dry to 10% final moisture, force dry to 10% final moisture and force dry to "oven-dry" to 0% moisture content. Density, tensile and WRV decreased through a recycling cycle. Results showed that fines contributed to density and tensile before and after recycling. Force-dried fines contributed most to the density and tensile before and after recycling because of the lower values of the fines-free pulp, but the least to the wet web strength. Scattering coefficient values were lowest for both air-dried pulps indicating higher bonding. He found that the bonding potential of the pulp in terms of
tensile, decreased with drying and higher drying severity of force-dry to "oven dry" lead to the largest decrease in the bonding potential of the pulp. For both of the force-dried pulps this loss in tensile was greatest for the pulps containing fines.

Matzke (47) found that drying reduced the brightness of unbleached mechanical and semi-bleached chemical pulps. The fines fractions showed poorer response to bleaching than the whole unclassified pulp.

Recently Wood and Karnis (48) (1991) determined the specific surface of mechanical pulp fines from turbidity measurements. It was suggested that specific surface of mechanical pulp fines decreases by 80-90 % during drying. (Other methods of specific surface determination are liquid permeability and nitrogen absorption measurements). They suggested that the importance of these tests lies in the influence of the fines fraction on drainage and wet web properties as well as dry strength and optical properties of the paper.

It can be proposed here that swelling of pulp is due to both long fibers and to the fines. For virgin pulp, the latter contribute in proportion to their weight more to the total swelling than do the fibers. It is well known that during beating, highly swollen fines are produced and pulp fibers become flexible. Since fines swell more, the increased swelling due to fines gives sheet a higher density which may give the sheet a greater potential to shrink during drying.

Repeated Recycling

Gottsching et al. (49) subjected four bleached chemical pulps by subjecting them to repeated paper-making (up to 12 times) with intermediate pulping. They found that
recycling impaired inter-fiber bonding while individual fiber strength was maintained over many recyclings. They stated that the relationship between breaking length and water retention values appears promising as a basis for commercial process control.

McKee (26) showed that for southern pine kraft pulp, refined to 325 csf and made into British handsheets, each repulping resulted in decrease in density, breaking length, burst, bonding strength and bonding area. Variables such as tear and Taber stiffness factor increased. Although the rate of change of properties with each repulping appeared to drop, there did not appear to be any evidence of a leveling off in properties after many repulpings (26,49).

Bobalek et al (50) subsequently demonstrated similar effects for five different furnishes for three repulpings under significantly less severe densification conditions, i.e., higher csf and zero wet pressing pressure. Bobalek did not find the same change in sheet density as seen by McKee (26). Zero span tensile increased with repulping, indicating that actual fiber strength development was continuing with refining in the absence of pressure. Consistent with McKee's findings, breaking length, and Scott Bond decreased, indicating reduced bonding (49,50).

Ruvo, Htun and Ehnrooth (1) stated that, mechanical beating of fibers improves the strength of fiber rather than damaging it. The strength of secondary fibers exhibited a drastic decrease only during the first cycle while in the next cycle minor decreases took place (which may be explained by factors such as contaminations and an increase proportion of fines).
It has been established that fines are important constituent of the papermaking fibers. Fines contribute not only towards strength and optical properties of paper, but also wet web properties. The ability of fines to improve bonding has been linked to their higher surface area and higher swelling power than the long fiber. Higher water retention values of fines are also attributed to higher swelling ability of fines. Higher surface area and greater ability to form bonds make fines more active towards bond formation. Drying process involved in recycling causes an effect usually known as “hornification”. Due to this effect, the fibers and fines become stiffer, losing their ability to conform during bond formation. The papermaking fibers also lose their swelling ability which is supposed to be due to permanent closure of pores and healing of the cracks in the fiber structure. The reduced swelling due to recycling results in reduced dry strength and wet strength properties. Repeated recycling can result in loss of paper and pulp properties even more although much of this loss occurs in the first recycle. As the fines swell more than the long fibers, the effects of recycling on fines become important, if fines are retained during recycling. The properties of the recycled pulps and paper can vary depending upon the method used for drying.
CHAPTER III

PROBLEM STATEMENT AND OBJECTIVES

Fines contribute to the strength of the paper made from fibers and fines due to their higher swelling and their ability to promote bonding between fibers. During recycling, drying reduces the swelling of the fibers, leading to the loss of strength and opacity in the recycled paper. The effect of drying on the structures and properties of the fibers and fines individually is not clear. Secondly, the effect of intensity of drying (through recycling) on the fibers and fines has to be assessed. An understanding of drying effect would allow the optimization of drying conditions and extent. The specific objectives of this research are: (a) To evaluate the contributions of fibers and fines to the virgin and the recycled paper properties, (b) To determine the effects of recycling and drying intensity on the properties of virgin and recycled pulps and papers, and (c) To develop models explaining the impact of drying conditions and fines content on paper as well as pulp properties.
CHAPTER IV

EXPERIMENTATION

Experimental Design

The objective of this project was to evaluate the contributions of the long fibers and fines towards never-dried virgin and recycled pulp and paper properties. In addition, the effects of drying intensity on the properties of pulps containing different amount of fines were evaluated.

Fines content produced during refining were added to long fibers to estimate the effect of various parameters and recycling conditions. The effects due to fines, fibers and recycling were studied by evaluating properties of recycled and original, non-recycled pulps (and papers). The effects of drying intensity were evaluated by changing drying conditions of papers with no added fines and papers containing increasing amounts of fines.

Experimentation involved pulp selection, refining, fines separation, controlled addition of fines to fibers, stock testing, paper production, and testing. This was followed by re-dispersion of these paper samples, stock testing, paper production and testing.

Figure 1 shows that fines passing through 100-mesh screen in the float washer were added to the long fibers (separated using 100-mesh screen) in 0, 10, 20, and 40% proportion.
Figure 1. The Process Design.
After testing these formulations for pulp and paper properties the handsheets were individually recycled. The handsheets were dried at three different levels of drying intensity as described in the Figure 1. The recycled sheets were dried at only two levels of drying intensity as shown in the Figure 1. The medium drying intensity level did not produce consistent results and thus was omitted during the recycling process. The recycled samples were also tested for pulp and paper properties.

Since this study involved the evaluation of contribution of cellulosic fibers and fines, bleached kraft pulp was used for the entire study. Softwood bleached kraft pulp was selected for this study. Softwood pulp responds better to refining and fiber development than the hardwood pulp. Two hundred pounds of bleached kraft pulp was supplied by the Consolidated Paper, Wisconsin Rapids at 50 percent consistency and had the following composition:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jackpine and White Pine</td>
<td>55%</td>
</tr>
<tr>
<td>Norway Pine</td>
<td>16%</td>
</tr>
<tr>
<td>Mixed Northwestern Softwoods (with Ponderosa Pine)</td>
<td>20%</td>
</tr>
<tr>
<td>Tamrock</td>
<td>3%</td>
</tr>
<tr>
<td>Balsam</td>
<td>5%</td>
</tr>
<tr>
<td>Spruce</td>
<td>1%</td>
</tr>
</tbody>
</table>
Phase 1: Pulp Preparation and Testing

Never dried pulp was refined to 600 csf level. Long fibers retained on 100-mesh screen of the Float Washer were saved and the fines were discarded. Another portion of never dried pulp was separately refined to 100 csf to increase the fines content. The latter pulp was run through the Float Washer and fines passing through 100-mesh screen of the Float Washer were collected. Pulp slurries were prepared by adding fines to the long fibers at 0, 10, 20, and 40%. The dispersions were evaluated for fiber length distribution, freeness, and water retention values (WRV). The pulps were also tested for wet web strength by making handsheets and testing the strength at different consistencies.

Phase 2: Handsheet Production and Testing

Handsheets were prepared from the above dispersions and were dried at three different drying intensity levels. The conditions for three levels of drying were experimentally determined so as to dry the sheet to a point of certain moisture content. The three different drying levels were selected as: (1) Low drying: Air drying at room temperature; (2) Medium drying: Drying at 220°F to a final moisture level of 10%, leaving the rest of the moisture to evaporate at room temperature; and (3) High drying: Drying at 220°F to lowest possible final moisture level, leaving the sheet at room temperature.

The sheets were conditioned at 73.4°F ±1.8°F and 50% ± 2% R.H. and then were tested for density, tensile strength, tear, opacity, scattering coefficient, absorption
coefficient and brightness. Wet web strength was measured by testing the wet sheets made from never dried pulp.

**Phase 3: Handsheet Recycling**

In this phase, the handsheets from the second phase were recycled individually without refining and the pulp slurries were tested for water retention values (WRV) and freeness. Recycled pulps were tested for wet web strength as described in the procedure. Handsheets were prepared from each pulp slurry and were dried at only two different drying intensity levels. The medium drying intensity level was omitted from the recycled phase as this level did not show any clear behavior in the phase 2. The results from the medium intensity drying were closer to those from either the low or the high intensity level of drying. Recycled handsheet samples were also tested for density, tensile strength, wet web strength, tear, scattering coefficient, absorption coefficient, opacity and brightness.

**Data Analysis**

Data were described graphically and statistically. Standard deviation of the replicates were calculated and were shown on the graphs as error bars, each representing one standard deviation above and below the average values. Data were analyzed statistically using $2^3$ factorial design. Paper properties, such as scattering coefficient, density, tear and tensile were individually considered as response variables in these designs. Three variables namely “recycling”, “fines addition” and “drying” were chosen as
independent variables. Each independent variable was considered at two conditions, "-" and "+". This factorial model will generate the effects due to main variables and the effects due to interactions between the variables. The independent variables and their conditions are shown in the Table 1.

Table 1

The $2^3$ Factorial Design

<table>
<thead>
<tr>
<th>Variable</th>
<th>-</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = Recycling</td>
<td>Virgin</td>
<td>Recycled</td>
</tr>
<tr>
<td>2 = Fines addition</td>
<td>0% (10%)</td>
<td>20% (40%)</td>
</tr>
<tr>
<td>3 = Drying</td>
<td>Air Dry</td>
<td>220°F, 4.25 min</td>
</tr>
</tbody>
</table>

Run Order | 1 | 2 | 3 | Response Variable
1 | - | - | - | (Paper properties such as density, tear, tensile and scattering coeff.)
2 | - | - | + |
3 | - | + | - |
4 | - | + | + |
5 | + | - | - |
6 | + | - | + |
7 | + | + | - |
8 | + | + | + |

* The values in the parenthesis represent different set of conditions for a similar design.
Experimental Procedure

Pulp Preparation and Fines Removal

One hundred pounds of never dried bleached softwood kraft pulp was dispersed in water at 1% consistency in the Black Clawson Hydrapulper. The Pulper was connected to a Beloit Double Disc refiner. After 10 minutes of mixing, the pulp was circulated through the disc refiner. Every five minutes, the refiner was stopped and freeness measurements were made. The pulp was refined to a level of 100 canadian standard freeness, csf. The pulp was then classified for removal of fines. Fines were separated from the long fiber using Sinclair Float Washer at 0.5% consistency. According to Britt and Unbehend (51), the single screen method avoids the cumulative error that is associated with multiscreen classifiers. Initial experimentation showed that it was very difficult to remove fines from the pulp refined at higher freeness levels. At higher freeness levels, the fines flow through the Float Washer was very little. In addition it was almost impossible to use 200 mesh screen in the Float Washer as the screen clogged up immediately, resulting in almost no flow through the screen. This suggests that the Sinclair Float Washer did not work very effectively to remove fines from high freeness stocks. A coarser screen was made by gluing a fourdinier forming fabric to the plastic ring of the broken Float Washer screen. The screen size was determined using a microscope. The hole size in the fabric was found out to be equivalent to that of the 100 mesh screen. So for this project the fines were defined as the ones passing through the 100 mesh screen in the Float washer.
Another batch of 100 pounds of pulp was mixed in the Black Clawson Hydrapulper and refined to a level of 600 csf. in the same way as before. This involved only 10 minutes of mixing and additional 5 minutes of refining in the disc refiner. Using the float washer with 100 mesh screen, the pulp at 0.5% consistency was classified to obtain the long fiber fraction.

**Preparation of Pulp-Fines Slurries**

Fines slurry at 3% consistency was added to long fiber fraction (also at 3% consistency) at 0, 10, 20, 40 % levels. The four slurries were diluted to 1.5% consistency and then dispersed for 5 minutes each in a mixer. Formaldehyde (1%) was added as a preservative and the pulp slurries were stored for two days.

**Pulp Evaluation**

**Wet Web Strength**

Initially it was proposed that the Brecht Wet Strength Tester would be used to test the wet web strength, but this instrument was not in working condition. Preliminary exploration with the Instron tensile tester turned out to be a promising method for testing the wet web strength as well. The only problem with this instrument was that it did not notice the break and thus the two jaws continued moving even after the break. The return button had to be hit in order to signal the instrument that the test was complete. The peak value of tensile was recorded as wet web strength.
Wet sheets were formed on the wire of a Noble and Wood machine and pressed at two different consistency levels. The pressed sheet was separated from the wire using a wet blotting paper, wetted with water and pressed in the Noble and Wood press using the same weight as that for pressing the sheet. This minimized the transfer of water from the sheet to the blotting paper. The 15% consistency level for the sheet was obtained by pressing the sheet with no weights, while approximately 25% consistency level was achieved using the normal press weights. Six strips from two sheets were tested at each consistency level. The strips were cut with a cutter which cut three strips at a time. Each strip was weighed, tested, weighed again and finally dried to determine the mean moisture level and weight. The size of the cut strip and the dried weight was used to determine the basis weight. A graph was plotted between consistencies averaged at 15% and 30% and strengths averaged at same moisture levels. A value of wet web strength at 22.5 % consistency was obtained through interpolation between 15% and 30% values.

Water Retention Values

Water retention values were obtained using a laboratory centrifuge. Approximately 0.8 gram o.d. (oven dry) fiber at 0.3% consistency was allowed to drain through an air vacuum flask. The cup (200-mesh screen) containing the sample was placed in a sealed container and centrifuged for 30 minutes at 900 times the force of gravity (900g) in the laboratory (11). After centrifuging, the sample was immediately weighed to obtain the wet weight. The sample was dried in the oven at 220°F to obtain the oven dried weight.
Water retention value WRV (11), was calculated as:

\[
\% \text{WRV} = \frac{\text{Wet weight} - \text{Oven dry weight}}{\text{Oven dry weight}} \times 100
\]

The units of WRV are: percentage water retained based on o.d. fiber.

Kajaani Fiber Length

Fines and long fiber fractions were analyzed for length and length distribution in the Kajaani FS-100 Fiber Size Analyzer. Three samples were tested for each of the four pulp mixtures and 100% fines.

Freeness

Freeness was tested according to TAPPI Standards T 227 om-93. Three measurements were made for each pulp type. The pulps of the recycled paper were also tested for freeness but only two measurements were made given the limited amount of the pulp.

Paper Preparation and Drying Conditions

Handsheets were prepared on Noble and Wood handsheet machine using a 150 - mesh screen. The grammage was maintained at approximately 62 g/m². The sheets were pressed in a Noble and Wood press.
Three different drying intensity levels were used to dry each of the virgin pulp types. The first level of drying intensity was air dry. Sheets on the 150 mesh wire itself were allowed to air dry under room temperature conditions. For medium level of drying intensity, the sheets were dried inside a 'Speed Dryer' to the final moisture content of 10%. This involved drying the sheet on the wire itself in the dryer maintained at 220°F for exactly 2.25 minutes. For high intensity drying, sheets were dried in the 'Speed Dryer' at 220°F for 4.25 minutes, until the final moisture content remained constant (at its lowest moisture value)(oven dry level). These temperatures and times conditions were determined on the basis of preliminary tests on experimental sheets at different temperatures and times and determining their moisture contents. It was difficult to maintain the final moisture levels at temperatures maintained over 220°F. All sheets were placed in the conditioning room (73.4°F ±1.8°F and 50% ±2% R.H.) for 24 hours before testing.

Physical Testing of Handsheets

The handsheets were tested to determine opacity and brightness using TAPPI Standards T425 om-91 (52) and T452 om-92 (53). Ten sheets were used to obtain an average of ten readings. The scattering coefficients and absorption coefficients were calculated using the Technibyne S4M Brightness Meter by entering the basis weight values for that set of handsheets. Caliper was measured using a motor-operated micrometer according to TAPPI Standard T411 om-84 (54). The average caliper and basis weight gave the density values. Tensile was measured using TAPPI Standard T494 om-88 (55).
Internal Tearing resistance of paper was measured using TAPPI Standard T414 om-88 (56) (eight replicates, each measurement involved 4 plies of sheets).

Recycling

The sheets prepared in the phase 2 (from virgin pulp) and the scraps saved from testing were recycled in the phase 3. All these sheets were separately soaked in distilled water for 24 hours and then mixed by hand at 1 % consistency. The samples were then separately disintegrated in a British Disintegrator for 15000 revolutions. No refining was involved in recycling the virgin paper. The recycled pulps thus obtained were tested for, water retention values, freeness and wet web strength. Paper sheets were prepared from these pulp samples using the low and high intensities, since the medium drying intensity gave very inconsistent results.

It is known that some amount of fiber loss during recycling is unavoidable. However kraft softwood pulps lost only small percentage of fiber material. White water was filtered and thus fiber loss during paper was calculated (based on weight) for few pulp slurries. It was found that the loss of fiber (or fines) was between 0.4 to 1.87% based on the original pulp. No appreciable difference was found between different intensity dried pulps.
CHAPTER V

RESULTS AND DISCUSSION

Characterization of Fines

In this project fines are considered as the particles passing through the 100-mesh screen in the Float Washer. Figure 2 shows that 75% of the fines (passing through 100 mesh screen) are less than 0.45 mm.

Figure 2. Population Distribution of Length of the Fines Passing Through 100-mesh.

The fines had a mean arithmetic average fiber length of 0.27 mm and a mean weighted average fiber length of 0.53 mm. A Kajaani FS-100 Fiber Analyzer was used for
the measurements. This method was limited by the fact that the smallest measured size was
0.02 mm. It is possible that some fines were smaller than 0.02 mm. Table 2 shows the
arithmetic and weighted average values for length of the various fiber/fines blends. Whole
pulp with most of the fines removed in the Float Washer is shown as 0% fines added, while
all fines pulp (no long fiber) is shown as 100% fines.

Table 2
Kajaani Fiber Analysis Data Showing Arithmetic Average and
Weighted Average Fiber Length

<table>
<thead>
<tr>
<th>Fines Added</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>40%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Arithmetic Average 1</td>
<td>0.84</td>
<td>0.76</td>
<td>0.71</td>
<td>0.50</td>
<td>0.27</td>
</tr>
<tr>
<td>*Arithmetic Average 2</td>
<td>0.82</td>
<td>0.70</td>
<td>0.73</td>
<td>0.61</td>
<td>0.27</td>
</tr>
<tr>
<td>*Mean Arithmetic Length</td>
<td>0.83</td>
<td>0.73</td>
<td>0.72</td>
<td>0.56</td>
<td>0.27</td>
</tr>
<tr>
<td>*Weighted Average 1</td>
<td>1.35</td>
<td>1.21</td>
<td>1.16</td>
<td>1.04</td>
<td>0.52</td>
</tr>
<tr>
<td>*Weighted Average 2</td>
<td>1.32</td>
<td>1.28</td>
<td>1.25</td>
<td>1.15</td>
<td>0.53</td>
</tr>
<tr>
<td>*Mean Weighted Length</td>
<td>1.34</td>
<td>1.24</td>
<td>1.20</td>
<td>1.10</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*The fiber length values are in mm.

Figure 3 shows the population distribution of the various fiber/fines blends made by
controlled addition of fines to the long fibers. The figure shows that the average fiber
length decreased linearly with the fines addition. Britt Jar measurements showed that the
Sinclair Float Washer treated pulp still had about 1.25% fines which passed through the
200-mesh perforated plate of the Britt Jar. This suggests that the Sinclair Float Wash did not remove all the fines from the stock.

![Graph showing weighted and arithmetic average fiber lengths at different fines addition levels.](image)

**Figure 3.** Weighted and Number Average Fiber Lengths at Different Fines Addition Levels.

**Freeness and Water Retention Values (WRV)**

Table 3 shows the data for the freeness and the water retention values of the virgin and the recycled pulps. The standard deviation (STD) and the coefficient of variation (CV), which is defined as the standard deviation /mean * 100, were calculated to determine the variability of the replicates. The low coefficient of variation values (most values are less than 2) show that the freeness and water retention values tests had good reproducibility.
Table 3

The Freeness and Water Retention Values of Virgin, Low Intensity Dried and High Intensity Dried Pulps

<table>
<thead>
<tr>
<th>Pulp Type</th>
<th>Virgin</th>
<th>*Recy., L</th>
<th>*Recy., H</th>
<th>Virgin</th>
<th>*Recy., L</th>
<th>*Recy., H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fines 0%</td>
<td>611</td>
<td>645</td>
<td>657</td>
<td>190.2</td>
<td>146.2</td>
<td>152.3</td>
</tr>
<tr>
<td></td>
<td>622</td>
<td>638</td>
<td>660</td>
<td>191.0</td>
<td>145.3</td>
<td>150.0</td>
</tr>
<tr>
<td></td>
<td>594</td>
<td>622</td>
<td></td>
<td>194.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD/MEAN</td>
<td>14.1/609</td>
<td>4.9/642</td>
<td>2.1/658</td>
<td>2.2/192</td>
<td>0.6/146</td>
<td>1.6/151.2</td>
</tr>
<tr>
<td>CV, %</td>
<td>2.320</td>
<td>0.772</td>
<td>0.322</td>
<td>2.200</td>
<td>0.600</td>
<td>1.600</td>
</tr>
<tr>
<td>Fines 10%</td>
<td>504</td>
<td>453</td>
<td>627</td>
<td>228.2</td>
<td>155.8</td>
<td>173.5</td>
</tr>
<tr>
<td></td>
<td>513</td>
<td>449</td>
<td>615</td>
<td>225.1</td>
<td>154.0</td>
<td>172.1</td>
</tr>
<tr>
<td></td>
<td>512</td>
<td></td>
<td></td>
<td>227.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD/MEAN</td>
<td>4.9/510</td>
<td>2.8/451</td>
<td>8.5/621</td>
<td>1.6/227</td>
<td>1.3/155</td>
<td>1.0/173</td>
</tr>
<tr>
<td>CV, %</td>
<td>0.968</td>
<td>0.627</td>
<td>1.366</td>
<td>0.712</td>
<td>0.822</td>
<td>0.556</td>
</tr>
<tr>
<td>Fines 20%</td>
<td>332</td>
<td>393</td>
<td>520</td>
<td>245.0</td>
<td>188.5</td>
<td>198.5</td>
</tr>
<tr>
<td></td>
<td>331</td>
<td>397</td>
<td>532</td>
<td>256.4</td>
<td>188.0</td>
<td>199.0</td>
</tr>
<tr>
<td></td>
<td>338</td>
<td></td>
<td></td>
<td>268.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD/MEAN</td>
<td>3.8/334</td>
<td>2.8/395</td>
<td>8.5/526</td>
<td>11.8/257</td>
<td>0.4/188</td>
<td>.4/199</td>
</tr>
<tr>
<td>CV, %</td>
<td>1.135</td>
<td>0.716</td>
<td>1.613</td>
<td>4.598</td>
<td>0.188</td>
<td>0.178</td>
</tr>
<tr>
<td>Fines 40%</td>
<td>138</td>
<td>315</td>
<td>359</td>
<td>280.0</td>
<td>208.3</td>
<td>230.0</td>
</tr>
<tr>
<td></td>
<td>128</td>
<td>312</td>
<td>326</td>
<td>283.9</td>
<td>204.0</td>
<td>218.0</td>
</tr>
<tr>
<td></td>
<td>142</td>
<td></td>
<td></td>
<td>284.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD/MEAN</td>
<td>7.2/136</td>
<td>2.1/314</td>
<td>23.3/342.5</td>
<td>2.5/283</td>
<td>3.0/206</td>
<td>8.5/224</td>
</tr>
<tr>
<td>CV, %</td>
<td>5.302</td>
<td>0.677</td>
<td>6.813</td>
<td>0.889</td>
<td>1.475</td>
<td>3.788</td>
</tr>
</tbody>
</table>

*Recy., L means low intensity dried virgin was recycled, while Recy., H means high intensity virgin was recycled.
Figure 4 shows that the freeness decreased with the addition of fines content. The higher surface area of the fines probably filled some of the voids of the fiber mat during drainage on the wire resulting in decreased drainage and freeness. The deceased freeness due to the addition of fines is an effect similar to that of refining. Ingmanson and Andrews (57) found a direct relationship between refining time and specific surface area of fines.

![Graph showing the freeness of the Virgin and Recycled Pulps at various fines addition levels.](image)

Figure 4. The Freeness of the Virgin and Recycled Pulps at Various Fines Addition Levels.

For the recycled pulps, the freeness also decreased with the fines content. The freeness values of recycled pulps were higher than the corresponding virgin pulps, but this effect was significant only for pulps recycled from paper dried at high intensity (Recy., H: High Intensity Dried Virgin). Considering the standard deviation and coefficients of variation values, the freeness of the pulp where low intensity dried virgin was
recycled (Recy., L: Low Intensity Dried Virgin) were not significantly different from the corresponding virgin ones, except at the 40% fines level. The increase in the freeness was expected, as no refining was involved during recycling. The loss of fines during recycling could also have lowered the freeness. Howard and Bichard (58) also found an increase in freeness on recycling for their chemical pulps.

Water retention values increased (Figure 5) with the fines addition in virgin as well as the recycled pulps. Recycling gave a large decrease in WRV over that of virgin (never dried) pulp. The differences in WRVs due drying intensities involved in the recycling was very small.

![Figure 5: Centrifugal Water Retention Values for 100 g o.d. at 900 the Force of Gravity.](image)

The WRVs of the recycled pulps were about 20% to 28% lower than those of
virgin pulps as is clear in the Table 3. Consistent with the findings of Lundberg et al. (1), the effect of drying on WRV was greater than the effect of drying intensity. Ruvo et al. (2) found the water retention value of once dried fibers to be the same as that of the unbeaten virgin pulps. He stated that all the swelling gained in the beating of the fibers was lost as a result of drying. These authors found that higher drying temperatures reduced the swelling much further, but this effect was small as compared to that of the drying alone (1,2). Reduced bonding ability had traditionally been described as "irreversible hornification", implying a stiffening and/or hardening of the fiber during drying (18,26,59). It has been proposed that the loss of flexibility and plasticity of fiber is due to the reduced swelling capacity of the fiber once it has been dried into paper (1,45,59). The reduced swelling due to permanent healing of the pores in the cellulose structure as a result of drying could have resulted in lower WRVs for the recycled pulps (Figure 5).

Using fiber saturation point as a measure of swelling, Stone et al. found 30% loss in the swelling ability of kraft pulp due to drying (60). Stone et al. (18) and Lundberg et al. (1) attributed the reduced swelling to the irreversible closure of large pores and healing of the cracks in the cell wall during drying (1,18,60). It was believed by these authors that drying promoted the healing of cracks and thus once dried fibers had less tendency to delaminate during beating than the virgin fiber.

As the freeness decreased and water retention values increased with the addition of fines, freeness can be plotted against WRVs of the different pulps (Figure 6). Figure 6 does show that WRV and freeness were more or less linearly related for the same pulp type.
For the same freeness, the water retention values of the recycled pulps were lower than the corresponding virgin pulps. One advantage of this phenomenon could be the reduced water drying energy for the recycled pulps, although it has to be commercially evaluated to see the actual benefits in the energy savings.

Properties of Virgin and Recycled Papers

Table 4 shows the properties of virgin as well as the recycled paper, the latter being obtained by recycling the low dried paper. Table 5 shows the properties of the recycled paper when high dried paper was recycled.
<table>
<thead>
<tr>
<th>Fines Added</th>
<th>Pulp type, Drying Intensity</th>
<th>Density, g/cm³</th>
<th>Tear Index, mN-m/²/g</th>
<th>Tensile Index, Nm/g</th>
<th>Brightness, %</th>
<th>Opacity, %</th>
<th>Scatter Coeff, m²/g</th>
<th>Absorption Coeff, m²/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>virgin, low</td>
<td>0.4258</td>
<td>18.94</td>
<td>35.63</td>
<td>79.32</td>
<td>79.30</td>
<td>36.29</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>virgin, high</td>
<td>0.4334</td>
<td>22.14</td>
<td>35.10</td>
<td>79.90</td>
<td>80.23</td>
<td>37.28</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>recy, low</td>
<td>0.4080</td>
<td>22.87</td>
<td>32.66</td>
<td>79.79</td>
<td>80.99</td>
<td>36.87</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>recy, high</td>
<td>0.4360</td>
<td>16.06</td>
<td>26.36</td>
<td>80.07</td>
<td>81.36</td>
<td>39.53</td>
<td>0.38</td>
</tr>
<tr>
<td>10%</td>
<td>virgin, low</td>
<td>0.4571</td>
<td>18.40</td>
<td>44.38</td>
<td>78.91</td>
<td>78.61</td>
<td>34.37</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>virgin, high</td>
<td>0.4462</td>
<td>20.05</td>
<td>41.06</td>
<td>78.69</td>
<td>78.58</td>
<td>37.76</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>recy, low</td>
<td>0.4370</td>
<td>23.10</td>
<td>36.06</td>
<td>77.64</td>
<td>80.92</td>
<td>36.71</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>recy, high</td>
<td>0.4770</td>
<td>17.52</td>
<td>35.08</td>
<td>77.51</td>
<td>81.09</td>
<td>39.23</td>
<td>0.44</td>
</tr>
<tr>
<td>20%</td>
<td>virgin, low</td>
<td>0.5360</td>
<td>15.14</td>
<td>55.32</td>
<td>72.47</td>
<td>77.51</td>
<td>32.22</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>virgin, high</td>
<td>0.5088</td>
<td>15.54</td>
<td>52.77</td>
<td>73.47</td>
<td>78.32</td>
<td>36.16</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>recy, low</td>
<td>0.3850</td>
<td>15.52</td>
<td>47.04</td>
<td>74.45</td>
<td>78.65</td>
<td>34.95</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>recy, high</td>
<td>0.4220</td>
<td>16.37</td>
<td>42.97</td>
<td>74.32</td>
<td>79.62</td>
<td>37.93</td>
<td>0.54</td>
</tr>
<tr>
<td>40%</td>
<td>virgin, low</td>
<td>0.5560</td>
<td>11.98</td>
<td>60.03</td>
<td>61.93</td>
<td>72.05</td>
<td>26.27</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>virgin, high</td>
<td>0.5284</td>
<td>12.96</td>
<td>59.00</td>
<td>62.42</td>
<td>73.70</td>
<td>30.65</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
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<td>0.4450</td>
<td>12.56</td>
<td>48.97</td>
<td>68.15</td>
<td>78.70</td>
<td>34.04</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>recy, high</td>
<td>0.5060</td>
<td>13.08</td>
<td>47.06</td>
<td>67.38</td>
<td>82.35</td>
<td>39.01</td>
<td>0.90</td>
</tr>
<tr>
<td>Fines Added</td>
<td>Pulp type, Drying Intensity</td>
<td>Density, g/cm^3</td>
<td>Tear Index, mN-m^2/g</td>
<td>Tensile Index, Nm/g</td>
<td>Brightness %</td>
<td>Opacity %</td>
<td>Scatt. Coeff. m^2/g</td>
<td>Abs. Coeff. m^2/g</td>
</tr>
<tr>
<td>-------------</td>
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<td>--------------</td>
<td>-----------</td>
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<td>------------------</td>
</tr>
<tr>
<td>0%</td>
<td>virgin,low</td>
<td>0.4258</td>
<td>18.94</td>
<td>35.63</td>
<td>79.32</td>
<td>79.30</td>
<td>36.29</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>virgin,high</td>
<td>0.4334</td>
<td>22.14</td>
<td>35.10</td>
<td>79.90</td>
<td>80.23</td>
<td>37.28</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>recy,low</td>
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<td>15.75</td>
<td>26.91</td>
<td>79.61</td>
<td>79.72</td>
<td>38.32</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>recy,high</td>
<td>0.3850</td>
<td>17.21</td>
<td>24.86</td>
<td>79.86</td>
<td>81.93</td>
<td>40.59</td>
<td>0.39</td>
</tr>
<tr>
<td>10%</td>
<td>virgin,low</td>
<td>0.4571</td>
<td>18.40</td>
<td>44.38</td>
<td>78.91</td>
<td>77.33</td>
<td>34.37</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>virgin,high</td>
<td>0.4462</td>
<td>20.048</td>
<td>41.061</td>
<td>78.69</td>
<td>78.34</td>
<td>37.76</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>recy,low</td>
<td>0.4470</td>
<td>16.35</td>
<td>33.34</td>
<td>78.84</td>
<td>80.84</td>
<td>37.98</td>
<td>0.45</td>
</tr>
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<td></td>
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<td>0.5070</td>
<td>24.78</td>
<td>33.34</td>
<td>78.22</td>
<td>81.66</td>
<td>40.2</td>
<td>0.42</td>
</tr>
<tr>
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<td>0.5360</td>
<td>15.14</td>
<td>55.32</td>
<td>72.47</td>
<td>77.91</td>
<td>32.22</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>virgin,high</td>
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<td>15.536</td>
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<td>73.47</td>
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<td>74.57</td>
<td>78.76</td>
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<td>0.51</td>
</tr>
<tr>
<td></td>
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<td>0.3790</td>
<td>15.88</td>
<td>44.51</td>
<td>74.93</td>
<td>80.06</td>
<td>39.94</td>
<td>0.58</td>
</tr>
<tr>
<td>40%</td>
<td>virgin,low</td>
<td>0.5560</td>
<td>11.98</td>
<td>60.03</td>
<td>61.93</td>
<td>72.05</td>
<td>26.27</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>virgin,high</td>
<td>0.5284</td>
<td>12.96</td>
<td>58.997</td>
<td>62.42</td>
<td>73.7</td>
<td>30.65</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>recy,low</td>
<td>0.4490</td>
<td>12.96</td>
<td>47.06</td>
<td>62.56</td>
<td>83.68</td>
<td>35.85</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>recy,high</td>
<td>0.5050</td>
<td>14.21</td>
<td>47.73</td>
<td>64.87</td>
<td>83.71</td>
<td>38.31</td>
<td>1.13</td>
</tr>
</tbody>
</table>
Density

Figure 7 indicates that the density of paper made from virgin pulp increased with the fines content. This confirms the results of various authors (11,14,16,17) that fines increase the density of paper. Increased density could be due to filling of voids with the fines material as well as increased bonding resulting from increased bonded area due to fines. As shown earlier (Figure 5) the fines offered higher WRVs (WRV is believed to be a measure of swelling ability of fibers and fines) (17,18,20) than the long fibers thus facilitating bonding. Increased bonding due to fines would give more densely packed structures resulting in increased density.

![Graph showing densities of papers made from low intensity dried virgin and low intensity dried recycled pulps at various fines addition levels.](image)

**Figure 7.** Densities of Papers Made From Low Intensity Dried Virgin and Low Intensity Dried Recycled Pulps at Various Fines Addition Levels.
Figure 7 shows that the density of paper made from the low intensity dried recycled pulp (involving low intensity dried virgin) also increased with fines, but these values were always lower than the values for virgin fibers at all fines addition levels. As with the WRVs, the density of the recycled pulps decreased (due to recycling) due to reduction in swelling ability of pulp. Reduced swelling would not only lead to stiffening of the fibers and fines, but also the reduced bonding potential and thus less compaction. Also these stiff and less conformable recycled fibers (and fines) would be bulky and thus would lead to less dense paper. The slope of the line (Figure 7) for the recycled pulps was lower than that for the virgin pulps. For the recycled pulp, the effect of increased density due to fines was not as great as it was in the case of virgin pulp. This means that the effect of recycling in terms of decreased density becomes more pronounced as the fines level increase in the pulp. This means than the effect of recycling in terms of reduced swelling and stiffening is more pronounced in case of fines as compared to that of fibers. McKee (26) and Howard (59) also found a decrease in density due to first recycling by about 4 % with lower decreases during subsequent recycles.

Before going into further discussion about the effect of variables on paper properties, it is necessary to acknowledge the limitation of the drying methods involved in this study. It is well known that the properties of paper are greatly dependent on its equilibrium moisture content (61,62). Paper is a hygroscopic material and thus establishes equilibrium moisture with the surrounding air. The final moisture content will depend on whether the sheet approached the equilibrium from a more dry state or a moist
state. This phenomenon called "Hysteresis" (Figure 8) (61,62,63) was extensively studied by Wink W.A. (62). Relative humidity and temperature can significantly affect paper properties (62). So in order to avoid "Hysteresis", TAPPI Standard method T402 om-93 (63) suggests preconditioning (10-35% RH and 72-104°F) which will establish moisture content within 0.15%. However preconditioning step may often be eliminated for mill process control and for one laboratory purposes (63). It further states that paper or board if dried to a moisture content below its level in equilibrium with 50% RH, preconditioning may not be necessary.

Typical moisture sorption isotherms for pulp and paper are shown in Figure 8 (62).

![Figure 8. Typical Moisture Sorption Isotherms for Pulp and Paper (62).](image)
For cellulosic materials that had never been dried, the first complete desorption curve A and the first complete absorption curve B define the outer boundaries of an equilibrium area. The moisture contents for subsequent relative humidity (RH) cycles fall within boundaries of an equilibrium area (62). Wink (62) stated that as paper does not normally approach 0% moisture, the effect of hysteresis is smaller than that depicted by Figure 8. At temperature up to 220°F and at constant relative humidity, a linear relation exists between the logarithm of the moisture content and the reciprocal of the absolute temperature. Wink (62) using bleached sulfite pulp induced relative humidity cycles between 48% and 52.4%. He found that respective moisture values remained constant following an exposure to relative humidity of 40%. He also found that changes in basis weight, tensile and tear due to relative humidity were 0.3%, 2.3% and 2.8% respectively. Furthermore he found that after excursion to 93, 25 and 50% RH, the tensile of kraft pulp increased only by 3%.

In this project the sheets were made in the same laboratory and were dried at either high temperature (220°F) or in a closed cabinet (air Dry) (and stored in Ziplock plastic bags after drying). However it is possible that air dried sheets approached the equilibrium moisture content from higher moisture (down curve in Figure 8). For high temperature drying, the equilibrium moisture content was approached from lower moisture content (up curve in Figure 8). As a result, the air dried (low intensity drying) should have attained higher final moisture than high temperature dried (high intensity drying) pulps. Different
moisture contents in the sheets could have resulted in variation in the paper properties.

Taking density as a response variable, $2^3$ factorial design (Table 1) was applied to the density values at 0% and 20% fines level for both virgin and recycled pulps. The factorial design and the conditions for the variables are shown in Table 1. Figure 9 shows the normal probability plot for density (Fines = 0% and 20%), fitting a full model. The full factorial model takes into account not only the main variables, but also the 2-way and 3-way interactions between the variables.

Normal probability plots help to determine the importance of the variables and their interactions. If all the effects are insignificant, the normal probability plot will be linear. Effects which are "outliers" are usually considered significant.

![Figure 9. Normal Probability Plot of the Effect of the Variables on Density (Fines = 0% and 20%).](image)
Figure 9 shows that 3-way interactions and some 2-way interactions were insignificant, while interaction fines*recycling (AC) was significant. The main effects of the variables seem significant in Figure 9. The main effects of the variables on a response variable such as density should be individually interpreted only if there is no evidence that the variable interacts with the other variables. When there is an evidence of interactions, the interacting variables should be considered with the other significant or near significant main effects. Taking only the significant main effects and interactions into consideration, a fitted factorial model will better estimate the effects than those obtained by fitting the full model.

Table 6 was obtained by taking into account the main effects (fines, recycling and drying intensity) and the interactions between fines and recycling. These effects were “outliers” in the normal probability plot, Figure 9.

Table 6

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@ Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.03725</td>
<td>0.00038</td>
<td>0.007107</td>
<td>62.52</td>
<td>0.000</td>
</tr>
<tr>
<td>Fines</td>
<td>0.01125</td>
<td>0.001863</td>
<td>0.007107</td>
<td>2.62</td>
<td>0.079</td>
</tr>
<tr>
<td>Drying</td>
<td>-0.06325</td>
<td>0.0562</td>
<td>0.007107</td>
<td>0.79</td>
<td>0.486</td>
</tr>
<tr>
<td>Recycling</td>
<td>-0.05575</td>
<td>0.03163</td>
<td>-0.007107</td>
<td>-4.45</td>
<td>0.021</td>
</tr>
<tr>
<td>Fines*Recy.</td>
<td>-0.05575</td>
<td>0.02788</td>
<td>0.007107</td>
<td>-3.92</td>
<td>0.029</td>
</tr>
</tbody>
</table>

$^5$Fines = Fines addition is often mentioned as fines in the discussion.

$^6$Fines*Recy. = Interactions between fines and recycling.

@ Std Coeff. = Standard Coefficient.
If the P value for an effect is less than 0.05, it means that the effect is significant at 95% confidence level. The P values (Table 6) show that although drying intensity did not have any effect, recycling had a significant effect on density. The effect due to fines is considered significant at 90% confidence level as the P value is 0.079 (less than 0.1).

Table 7 shows that P values due to main effects and interactions were small, the former having a value just over 0.05.

Table 7

Analysis of Variance for Density (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>0.011029</td>
<td>0.0036765</td>
<td>9.10</td>
<td>0.051</td>
</tr>
<tr>
<td>2-Way Interactions</td>
<td>1</td>
<td>0.006216</td>
<td>0.0062161</td>
<td>15.38</td>
<td>0.029</td>
</tr>
<tr>
<td>Residual Error</td>
<td>3</td>
<td>0.001212</td>
<td>0.0004041</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>0.018458</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*DF = Degrees of Freedom,
Seq. SS = Sequential Sum of Squares
*Adj MS = Adjusted Mean Squares

The higher order interactions (three-way interactions) were considered insignificant in the fitted model, these effects measure the differences arising due to error.

The residual error was calculated by Minitab using the variables not considered in the fitted model, such as 3-way interactions ABC, and the other two 2-way interactions AB and BC (see Figure 9).
An estimated value for variance for the effect of the variables could be calculated as (66):

\[(effect\ ABC)^2 + (effect\ AB)^2 + (effect\ BC)^2\]

\[
\text{Var.}(\text{effect}) = \frac{\text{Degrees of Freedom}}{\text{Degrees of Freedom}}
\]

The estimated standard error of the variable then is:

\[
\text{STD Error} = (\text{Var.}(\text{effect}))^{1/2}
\]

Figure 10 shows the normal probability plot obtained by fitting the full model at different fines levels, given that the conditions for other variables the same. For this model the conditions for the variable fines are given in parenthesis in Table 1. This model is the same as the earlier model (Figure 9, Table 6 and 7) in terms of behavior of the pulp. However this model is different in terms of conditions for the variable ‘fines’. In this model, the difference between the lower (10%) and higher (40%) level of fines is 30%, instead of a difference of 20% fines between lower (0%) (-), and high level (20%) (+) in the earlier model). As is evident from Figure 10, only the main effects look important and all interactions are insignificant.

Table 8 and 9 were obtained by considering just the main effects in the fitted model. The only factor that was significant to a level of 90% confidence level was the effect due to fines level, other factors being insignificant (Table 8). Table 9 shows that the main effects were not statistically significant.
Figure 10. Normal Probability Plot of the Effect of the Variables on Density (Fines = 10% and 40%).

Table 8

Estimated Effects and Coefficients for Density (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.01276</td>
<td>37.75</td>
<td>0.000</td>
</tr>
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<td>Fines</td>
<td>0.05452</td>
<td>0.02726</td>
<td>0.01276</td>
<td>2.14</td>
<td>0.099</td>
</tr>
<tr>
<td>Drying</td>
<td>0.01563</td>
<td>0.00781</td>
<td>0.01276</td>
<td>0.61</td>
<td>0.573</td>
</tr>
<tr>
<td>Recycling</td>
<td>-0.03068</td>
<td>-0.01534</td>
<td>0.01276</td>
<td>-1.20</td>
<td>0.296</td>
</tr>
</tbody>
</table>

The insignificance of the P value for the main effects (Table 9) is mainly due to insignificance of the variables drying and recycling and not due to the insignificance of the variable 'fines'. 
Figure 11 shows that for all the virgin and the recycled pulps, the density values were similar at low fines levels. At higher fines level, the effect of recycling appeared significant. Figure 11 shows that recycling had a larger effect on density than the intensity of drying. It has been hypothesized that low intensity dried pulps could have a higher moisture content than the high intensity pulps. Higher moisture left in the low intensity dried pulps should produce lower density as the moisture would allow the fibers to swell (higher caliper). Figure 11 shows that for recycled pulps and at 40% fines addition level, the low intensity dried pulp has lower density than high intensity pulp. However, for virgin pulps at 10, 20, 40% fines, low intensity dried pulps had higher densities than high intensity pulps. This is because higher intensity of dying could have overdried the sheets and could have destroyed most of the hydrogen bonds in the fiber network. Air drying method would leave enough moisture for the hydrogen bonds and thus would result in greater bonding and thus higher density.

Table 9
Analysis of Variance for Density
(Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>0.008316</td>
<td>0.002772</td>
<td>2.13</td>
<td>0.239</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>0.005208</td>
<td>0.001302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>0.013524</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 11. Densities of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
The contradiction between the effect due to different equilibrium moisture contents and the effect due to drying intensity could only be resolved by considering other paper properties.

Scattering Coefficient

Scattering coefficient of the virgin pulps as well as the recycled pulps generally decreased with the fines addition (Figure 12). Hawes et al. (5) and Lidholm (22) also found increases in scattering coefficients due to fines. As the fines were contributing more towards bonding than the long fibers, there was lesser surface area available to scatter the incident light, as the fines level increased. This resulted in lower scattering coefficient for the pulps with higher fines levels. It appears from the Figure 12, that the recycled pulps had higher scattering coefficient than the virgin pulps for the same fines level.

Figure 12. Scattering Coefficient of the Virgin and the Recycled Pulps as a Function of Fines Addition Level.
The behaviors of the recycled and the virgin pulps were common for both levels of intensity of drying (Figure 13). The high dried recycled pulps produced higher scattering coefficient than the low intensity dried recycled pulps. This result was expected, as higher intensity of drying could have reduced the bonding ability of the fines even more leading to higher scattering coefficient for high intensity dried recycled pulps. (High intensity of drying would lead to greater “hornification” and lesser hydrogen bonding in the recycled pulps). If low intensity dried pulps had comparatively higher moisture content (“Hysteresis”), the swelling of fiber would have resulted in bulkier sheet and thus greater surface area to scatter incident light (higher scattering coefficient). As this is not the case here, the effect due to drying intensity seems more reasonable than the effect due to different equilibrium moisture contents. This supports the earlier hypothesis that low and high intensity pulps probably had about the same equilibrium moisture content. Higher scattering coefficient (lower bonding) of the high intensity pulps supports the argument that drying intensity did have an effect on scattering coefficient.

Figure 13 shows that although scattering coefficient of both the virgins decreased with the addition of fines, the scattering coefficient for the recycled pulps decreased only to 20% fines. The ability of the fines to increase bonding decreases during recycling and this effect becomes more pronounced at higher fines levels. This effect was even more pronounced for 'recycled, high intensity drying' as the scattering coefficient even increased from 20% to 40% fines.
Figure 13. Scattering Coefficients of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
Taking scattering coefficient as response variable, $2^3$ factorial design can be applied considering the variables defined in the Table 1. For the following statistical analysis the conditions for the fines level were low and high at 0% and 20% respectively. From the normal probability plot (Figure 14), for the scattering coefficient it can be seen that the main effects are "outliers" and thus are important.

Figure 14. Normal Probability Plot of the Effect of the Variables on Scattering Coefficient (Fines = 0% and 20%).

Taking main effects A, B and C variables into account factorial design was applied which resulted in estimated effects and coefficients as described in the Table 10 and 11. Tables 10 shows that all the three main effects were significant at 95% confidence levels, because all the P values were less than 0.05. Table 11 shows a P value of 0.012, meaning that main effects were quite significant.
Table 10

Estimated Effects and Coefficients for Scattering Coefficient
(Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
</table>
| Constant | 36.384 | 0.2902      |             | 125.37    | 0.000
| Fines    | -2.137 | -1.069      | 0.2902      | -3.68     | 0.021
| Drying   | 2.682  | 1.341       | 0.2902      | 4.62      | 0.010
| Recycling| 1.792  | 0.896       | 0.2902      | 3.09      | 0.037

Table 11

Analysis of Variance for Scattering Coefficient (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>29.956</td>
<td>9.9852</td>
<td>14.82</td>
<td>0.012</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>2.695</td>
<td>0.6738</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>32.651</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The same $2^3$ factorial design was applied taking different conditions of low (-) (10%) and high (+) (40%) fines level. All other variables had the same conditions as described in Table 1.

The normal probability plot, Figure 15 shows that in addition to all the main variables the interaction fines*recycling is important.

Taking these four effects into consideration the factorial analysis produced very small P values for the effects (Table 12 and 13). This proves that not only the main
but also the interaction between fines and recycling (Fines*Recy.) were significant factors affecting scattering coefficient.

Figure 15. Normal Probability Plot of the Effect of the Variables on Scattering Coefficient (Fines = 10% and 40%).

Table 12
Estimated Effects and Coefficients for Scattering Coefficient (Fines = 10% and 40%)

| Term            | Effect | Coefficient | @Std Coeff. | t - Value | P
|-----------------|--------|-------------|-------------|-----------|---
| Constant        | 34.950 | 0.2191      | 159.51      | 0.000     |
| Fines           | -4.215 | -2.107      | 0.2191      | -9.62     | 0.002|
| Drying          | 3.525  | 1.762       | 0.2191      | 8.04      | 0.004|
| Recycling       | 5.375  | 2.688       | 0.2191      | 12.27     | 0.001|
| !Fines*Recy.    | 3.390  | 1.695       | 0.2191      | 7.74      | 0.004|
Table 13
Analysis of Variance for Scattering Coefficient (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>118.165</td>
<td>39.3883</td>
<td>102.55</td>
<td>0.002</td>
</tr>
<tr>
<td>2-Way Interactions</td>
<td>1</td>
<td>22.984</td>
<td>22.9842</td>
<td>59.84</td>
<td>0.004</td>
</tr>
<tr>
<td>Residual Error</td>
<td>3</td>
<td>1.152</td>
<td>0.3841</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>142.301</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 16 shows that at low levels of fines addition (10%), the recycling produced only about 2 m²/g increase in the scattering coefficient, but at higher level of fines addition (40%) this increase was about 9 m²/g. This supports the earlier proposed model that the effect of recycling on raising the scattering coefficient (hence lowering the bonding) was more pronounced at higher fines level.

Figure 16. Cube Plot of The Effect of Interaction of Fines Addition and Recycling on Scattering Coefficient (Fines = 10% and 40%).
Opacity and Brightness

Opacity and brightness should be discussed together because both these properties depend on scattering and absorption coefficients. Figure 17 shows the absorption coefficients of the virgin as well as the recycled pulps. Absorption coefficient increased as the fines levels increased. The increase in the absorption coefficient due to fines becomes larger as the fines level go up. Visually the fines appeared darker than the long fibers. This could be explained on the basis that fines having high surface area, absorbed iron from the non-ionized water used for stock preparation, resulting in darker color.

The differences between the recycled and virgin absorption coefficients (Figure 17) were small although some values crossed at 20%, implying that some of the recycled pulps had lower absorption coeff. than the virgin ones. Considering one standard deviation of variation between the replicates, the difference between the various pulp types seems insignificant. Small differences between the pulps could be due to contamination.

Figure 18 shows that opacity generally decreased as the fines level increased, for both virgin as well as recycled pulps. Optical properties of paper are usually discussed with reference to the theoretical model developed by Kubelka and Munk. The assumption of the Kubelka Munk theory (67) is that the optical properties of the paper, e.g., the reflectance factor of a single sheet over a black background \( R_o \), the reflectivity of an opaque pad of the material \( R_e \), the transmittance \( T \), and the opacity are functions of scattering coefficient absorption coefficient and grammage (68).
Figure 17. Absorption Coefficients of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
Figure 18. Opacity of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
Opacity increases with increasing scattering coefficient and with the increasing absorption coefficient. In this case the scattering coefficient decreased and absorption coefficient increased with the fines level (Table 4 and 5 and Figure 13 and 17). As the opacity decreased due to fines (Figure 18), it can be proposed that the effect of scattering coefficient due to fines overpowered the effect of absorption coefficient and thus the opacity generally decreased due to fines addition. The recycled pulps produced higher opacities (an effect consistent with higher scattering coefficient of recycled pulps), than the virgin pulps. It appears that for both virgin and recycled pulps, the higher intensity of drying corresponded to higher opacity. Reduced hydrogen bonding due to high intensity of drying could have resulted in increased scattering coefficient and thus increased opacity. If the low intensity pulps had relatively higher moisture content, that would have produced higher scattering coefficient and thus higher opacity. So it seems once again the two drying methods did not produce appreciable moisture content variations due to the effect of "hysteresis".

As with the scattering coefficient (Figure 13), the opacity of 'recy., high intensity dried' pulps increased over 20% fines addition (Figure 18). As discussed earlier, the reduced bonding of recycled pulps at higher fines level (40% fines addition) resulted in increased scattering coefficient (Figure 13) and thus increased opacity (Figure 18).

Brightness decreased with fines content in all cases as is evident in the Figure 19. As brightness increases with scattering coefficient but decreases with the absorption
Figure 19. Brightness of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
coefficient, fines addition resulted in lower brightness. The effect of recycling on brightness was not very clear, however for 40% fines the recycled values were marginally higher, suggesting that recycling resulted in higher brightness (an effect possibly due to increased scattering coefficient of the recycled pulps).

**Tensile Strength**

Figure 20 shows that tensile decreased through recycling in all cases of drying but always increased with the fines content (recycled as well as virgin pulps, Table 4 and 5). This confirms the results of various authors (7,13,14,16,17,23) that tensile increases with increasing fines. The increase in tensile due to fines was similar all cases. The tensile increased by about 10 Nm/g with 10% increase in the fines, but only to a level of 20% fines addition. Over 20%, the increase in tensile was only 5 Nm/g (or lower for recycled pulps) with the 20% increase in fines level. Corson (16) also observed that tensile increases more rapidly at lower fines level, but this effect diminishes at higher fines levels. Corson (16) actually found decreases in tensile (for virgin pulps) at fines level over 40%. Increased tensile due to increased level of fines could be explained on the basis of improved bonding in the sheets produced by fines. Fines also allow better distribution of stress and strain during the tensile testing procedure leading to higher tensile values. For both of the recycled pulps (Figure 20), the tensile tended to level off at over 20% fines.

At higher fines level the fines interfered with bonding leading to increased scattering coefficient and decreased tensile. It is hypothesized that the fines carried high
Figure 20. Tensile Index of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
moisture content in the virgin pulp (higher WRVs for the pulps with higher fines). Due to higher moisture content, the fines had larger swollen volume and thus their chances of fiber wall collapse during recycling were higher. Thus recycled fines was not as active and interfered with bonding, especially at higher fines levels. Figure 12 also shows that for both the virgin and the recycled pulps, lower intensity drying resulted in higher tensile. Assuming that the effect of different equilibrium moisture is there, low intensity dried pulps (due to their higher moisture) should produce lower tensile than the high intensity dried pulps. Once again this argument does not hold valid as higher intensity of drying resulted in degradation of the hydrogen bonds and thus lower tensile strength.

Bonding has been usually related to the swelling power of the pulp by many authors (1,18,20,30,45). Since WRV measures fiber swelling, it can be plotted against tensile index. When tensile strengths were plotted against WRVs (Figure 21), straight lines resulted, suggesting that WRVs (and swelling) and tensile have a linear relationship. Jayme (9) also found a linear relationship between water retention values and tensile. It can be proposed that the strength properties of the paper were mostly dependent on the ability of the fiber to swell before sheet formation.

The $2^3$ factorial design can be applied for tensile considering the conditions described in Table 1. Figure 22 shows the normal probability plot of the effect of the variables on tensile strength. Only the main effects appear to be significant because they are "outliers".
Figure 21. Relationship of Water Retention Value and Tensile Strength.

Figure 22. Normal Probability Plot of the Effect of Variables on Tensile Strength (Fines = 0% and 20%).
Taking only the main factors into consideration the $2^3$ factorial design was applied (Table 14 and 15). Table 14 and 15 show that effects due to the main variables (fines addition, drying intensity and recycling) were significant at 95% confidence level, because all the P values are less than 0.05. The F value for the main effects (Table 15) was quite large and the P value was very small suggesting that these variables had significant effect on the tensile strength.

Table 14

Estimated Effects and Coefficients for Tensile Strength (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>41.145</td>
<td>0.6533</td>
<td></td>
<td>62.98</td>
<td>0.000</td>
</tr>
<tr>
<td>Fines</td>
<td>17.411</td>
<td>8.706</td>
<td>0.6533</td>
<td>13.32</td>
<td>0.000</td>
</tr>
<tr>
<td>Drying</td>
<td>-3.689</td>
<td>-1.8448</td>
<td>0.6533</td>
<td>-2.82</td>
<td>0.048</td>
</tr>
<tr>
<td>Recycling</td>
<td>-7.125</td>
<td>-3.563</td>
<td>0.6533</td>
<td>-5.45</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 15

Analysis of Variance for Tensile Strength (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Source</th>
<th>&amp;DF</th>
<th>&amp;Seq. SS</th>
<th>&amp;Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>735.03</td>
<td>245.012</td>
<td>71.75</td>
<td>0.001</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>13.66</td>
<td>3.145</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>748.69</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For Figure 23, $2^3$ factorial design was applied for tensile at different conditions of low (10%) and high (40%) fines level (other variables recycling and drying
that only the effects due to variables fines and recycling were important.

Figure 23. Normal Probability Plot of the Effect of Variables on Tensile Strength (Fines = 10% and 40%).

Table 16 and 17 were obtained by considering three main variables in the fitted model.

Table 16

Estimated Effects and Coefficients for Tensile Strength (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>45.905</td>
<td>0.6465</td>
<td></td>
<td>71.11</td>
<td>0.000</td>
</tr>
<tr>
<td>Fines</td>
<td>15.220</td>
<td>7.610</td>
<td>0.6456</td>
<td>11.79</td>
<td>0.000</td>
</tr>
<tr>
<td>Drying</td>
<td>-0.710</td>
<td>-0.355</td>
<td>0.6465</td>
<td>-0.55</td>
<td>0.612</td>
</tr>
<tr>
<td>Recycling</td>
<td>-10.425</td>
<td>-5.212</td>
<td>0.6465</td>
<td>-8.07</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Table 17
Analysis of Variance for Tensile Strength (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>681.67</td>
<td>227.222</td>
<td>68.15</td>
<td>0.001</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>13.34</td>
<td>3.334</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>695.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16 and 17 clearly show that only the effects of fines and recycling on tensile (P = < 0.05) were significant. The variable drying intensity had no significant effect on tensile.

Tear Strength

Tear strength generally decreased (Figure 24) with the fines addition for both virgin and recycled pulps. Rief (11) also found that for virgin pulps tear increased with fines.

![Figure 24. Tear Strength of the Virgin and the Recycled Paper.](image)
This is because the increased bonding due to the presence of fines allowed more long fibers in the sheet to break (rather than the bonds) resulting in lesser work force required and thus lower tear force. Figure 26 shows that for the recycled pulps, the tear slightly increased before it started decreasing at 10% (a 40% decrease from 0% to 20% fines). The increase in tear due to recycling contradicts the findings of Ferguson (64), but supports the results of Howard (59). As the bonding decreased with recycling, certain amount of fines (as compared to no fines) could have allowed better stress distribution in the paper leading to increase in tear.

The normal probability plot of variables (Fines = 0%, 20%) Figure 25, shows that only important variable is fines.

Figure 25. Normal Probability Plot of the Effect of the Variables on Tear Strength (Fines = 0% and 20%).
Figure 26. Tear Index of Virgin and Recycled Pulps, Each at Low and High Drying Levels.
Table 18 shows that none of the effects were significant to a level of 95% confidence level. The effect of variable fines was only significant at the 90% confidence level. Table 19 shows a higher value of $P$ for the main effects suggesting very little effect due to main effects.

**Table 18**

Estimated Effects and Coefficients for Tear Strength (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient @Std Coeff</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>17.574</td>
<td>1.010</td>
<td>17.40</td>
<td>0.000</td>
</tr>
<tr>
<td>Fines</td>
<td>-4.858</td>
<td>-2.429</td>
<td>-2.40</td>
<td>0.074</td>
</tr>
<tr>
<td>Drying</td>
<td>-0.093</td>
<td>-0.046</td>
<td>-0.05</td>
<td>0.966</td>
</tr>
<tr>
<td>Recycling</td>
<td>-0.732</td>
<td>-0.366</td>
<td>-0.36</td>
<td>0.735</td>
</tr>
</tbody>
</table>

**Table 19**

Analysis of Variance for Tear Strength (Fines = 0% and 20%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>48.28</td>
<td>16.094</td>
<td>1.97</td>
<td>0.260</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>32.64</td>
<td>8.160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>80.92</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The same design can be applied taking 10% and 40% (fines addition levels) as conditions of low and high for the variable 'fines addition'.
The normal probability plot (Figure 27) shows again that the variable fines (an "outlier") was important.

Figure 27. Normal Probability Plot of the Effect of the Variables on Tear Strength (Fines = 10% and 40%).

The factorial design can be applied taking all main effects (Table 20 and 21). Table 20 shows that the effect of variable fines on tear was significant at 95% confidence level. The P value in the Table 18 (Fines = 0% and 20%) was larger than the P value in Table 20 (Fines = 10% and 40%), suggesting that the effect of fines content on tear was less important in the former case. As was clear in Figure 27 variable drying intensity and recycling did not produce significant effects in the fitted model (Table 20 and 21).
Table 20

Estimated Effects and Coefficients for Tear Strength (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>Coefficient</th>
<th>@Std Coeff.</th>
<th>t - Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>16.284</td>
<td>0.8172</td>
<td>19.93</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Fines</td>
<td>-7.327</td>
<td>-3.664</td>
<td>0.8172</td>
<td>-4.48</td>
<td>0.011</td>
</tr>
<tr>
<td>Drying</td>
<td>-0.762</td>
<td>-0.381</td>
<td>0.8172</td>
<td>-0.47</td>
<td>0.665</td>
</tr>
<tr>
<td>Recycling</td>
<td>0.873</td>
<td>0.436</td>
<td>0.8172</td>
<td>0.53</td>
<td>0.622</td>
</tr>
</tbody>
</table>

Table 21

Analysis of Variance for Tear Strength (Fines = 10% and 40%)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq. SS</th>
<th>Adj. MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Effects</td>
<td>3</td>
<td>110.07</td>
<td>36.690</td>
<td>6.87</td>
<td>0.047</td>
</tr>
<tr>
<td>Residual Error</td>
<td>4</td>
<td>21.37</td>
<td>5.343</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>131.44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wet Web Strength

Figure 28 is a plot of wet web strength of the fibers at different consistencies. The wet web strength at 22.5% consistency was obtained from Figure 28 by extrapolating between wet web strength values at 20% and 25% consistencies respectively.

Swanson (65) summarized studies which showed the development of strength (Campbell Effect) as the water is removed from the fiber network.
Figure 28. Wet Web Strength as a Function of Consistency.
At about 8% consistency the web is held together by surface tension forces arising from the menisci formed as the water layer recedes into the fibrous structure.

As long as the radius of curvature is large the principal force, $F$, pulling the fiber together is approximately given by:

$$F = rL$$

$r$ is surface tension in dynes per centimeter and $L$ is the length of line of contact between air, water, and fiber.

As the water recedes, a meniscus appears between two fibers and the compacting force acting on the fibers is:

$$F = 2rL$$

Finally at about 22-25% solids, sheet density increases due to the increased compaction forces. The magnitude of the pressure difference caused by surface tension can be given as:

$$P = \frac{2r}{X}$$

where $X$ is the thickness of the liquid film (or the distance between two fibers).

The pressure $P$, is inversely proportional to the film thickness. Fines are believed to act like fibrils (5) (due to their higher swelling) and thus help reducing the distance $X$ between the bonding surfaces.

Wet web strength increases with the fines level and has a straight line behavior for the virgin (undried) fibers (Figure 29). These results agree with those of various authors
Figure 29. Wet Web Strength as a Function of Fines Addition Level and Recycling.
Figure 29. shows that for low intensity dried recycled pulps, the wet web strength increased till 10% fines along with the virgin and then almost remained constant or decreased with the increasing levels of fines. The wet web strength of the high intensity dried pulps also behaved in the same way, but these values were lower than the low intensity dried recycled. Due to an effect called "hornification" involved in the recycling, the fines lost their bonding activity and did not form effective bridges and hence did not act well with fibers. Higher intensity (greater effect of hornification) of the drying produced even lower wet web strength than that produced by low intensity drying.

Higher tensile and higher wet web strength produced by low intensity dried pulps as compared to high intensity dried pulps supports the hypothesis that the drying methods did not produce exceptionally different equilibrium moisture contents in the pulps. The difference between pulps was due to different intensity of drying and not due to different equilibrium moisture contents ("Hysteresis").
CHAPTER VI

SUMMARY OF THE RESULTS

1. Fines content with arithmetic average size of 0.27 mm when added to long fibers, freeness decreased and water retention values increased (about 18% increase in WRV with 10% increase in fines). Water retention value (WRV) has been considered as a measure of swelling ability of fines. The WRVs of the various pulp types were linearly related to their freeness. For recycled pulps the relationship between WRV and freeness was similar although at the same freeness, the recycled pulps had 20% lower WRVs than the virgin. The decrease in the water retention value due to recycling is attributed to reduced swelling due to drying. The effect of recycling and drying on water retention values is more pronounced than the effect due to different drying intensities.

2. Density, tensile and absorption coefficient increased, while scattering coefficient, tear and brightness decreased with fines content. These results suggest increased bonding due to the presence of fines. Tensile was linearly related to WRVs. It is proposed that tensile strength of paper was dependent on the ability of the fibers and fines to swell before sheet formation. The tensile strength of pulps increased by about 10 Nm/g per 10% increase in fines but only to 20% fines addition. Over 20% fines, the tensile tended to level off with additional quantities of fines, especially the recycled fines. It is proposed that the reduced bonding ability of fines due to recycling lead to reduced tensile strength.
Reduced bonding due to recycling also appeared as increased scattering coefficient and tear strength and decreased density.

3. As drying resulted in reduced bonding, higher intensity of drying resulted in greater reduction in bonding. Higher intensity drying resulted in higher scattering coefficient, lower density and lower tensile (as compared to lower intensity drying). It is suspected that "Overdrying" condition that accompanied the high intensity resulted in "degradation" of the bonding (also bonding sites) in the fiber structure. In the case of low drying the bonding was not as affected as it was in the case of high intensity drying.

4. For virgin pulps, wet web strength increased with fines addition for virgin pulps suggesting that fines contribute to the wet web strength. For recycled fibers, wet web strength did not increase significantly, at least after 10% fines. It is believed that reduced bonding ability of fibers (and fines) resulted in reduced wet web bonding in the recycled pulps. High intensity drying lead to even greater reduction in the wet web strength. It is proposed that reduction in bonding sites and degradation of bonding (due to higher intensity of drying) resulted in reduced wet web strength.

5. Statistical analysis was applied to the data using $2^3$ factorial design. The effect of the main variables 'fines addition' and 'recycling' and their interactions on density were significant at 95% confidence level (Fines = 0% and 20%). Only the variable 'fines' was significantly influencing density at 90% confidence level when the model containing 10% and 40% fines was considered. All the three variables ('fines addition', 'recycling' and 'drying intensity') significantly influenced scattering coefficient at 95 % confidence levels.
(for the $2^3$ factorial model considering "Fines = 0% and 20%" as well as model considering "Fines = 10% and 40%"). For the response variable tear, only the variable 'fines addition' was significant between 90 (Fines = 0 and 20% fines) to 95% (Fines = 10, 40% fines) levels.

6. Opacity decreased with fines addition for the virgin pulps, while for the recycled pulps the opacity decreased only up to 20% fines and increased afterwards. The effect of scattering coefficient on opacity was found to be more important than the effect of absorption coefficient. As the scattering coefficient increased due to recycling, recycled pulps had higher opacity values than the virgins.
CHAPTER VII

CONCLUSIONS

1. Water retention Values (WRVs) of the softwood kraft pulps increased by about 18% with 10% increase in the fines level. The effect of increased WRVs due to fines was attributed to high swelling ability of fines. Recycling produced at least 20% decrease in the WRVs. WRVs of the recycled pulp decreased due to reduced swelling and thus reduced bonding. The effect of recycling on WRV was greater than the effect of drying intensity.

2. Density, tensile, wet web strength increased with the fines addition while scattering coefficient and tear and opacity decreased with fines addition. All these changes in the paper properties support the hypothesis that bonding increased with fines addition.

3. Drying process involved in the recycling lead to reduction in WRVs, tensile, density and wet web strength and increase in scattering coefficient and opacity. It is believed that reduced swelling ability of fibers and fines caused reduced bonding in the recycled pulps.

4. High intensity of drying resulted in greater decrease in WRVs, tensile, density and greater increase in scattering coefficient as compared to the low intensity drying. High intensity of drying involved high rate of drying as well as "overdrying". It is believed that either (or both) of these effects caused degradation of bonding leading to the above changes in the pulp and paper properties.
CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

1. Fines have been shown to be an important component of paper due to their contribution to bonding. One of the factors which influence the paper properties is average fiber size (length). It would be interesting to study the effects of fiber size distribution on the paper properties. Hardwood pulp (which usually consists of short fiber) if mixed with long fiber softwood would generate different pulp and paper properties than those depicted by this study. It would also be fruitful to study the effect of chemical nature of fines on various paper properties. For example studies should involve the contribution of fines generated by different pulping methods. In addition, if long fibers are modified (chemically) to behave differently than fines, that would help separating the effect of fines and fibers in terms of pulp and paper properties.

2. More research is needed on the effects of drying on fiber and fines and paper properties. In this study the effect of drying involved not only the effect due to temperature (rate of drying), but also the effect due to "overdrying". If a paper is dried to same final moisture content, but to a different drying rate (Impulse drying verses air dry) it would lead to different results than those expected when paper is dried at same drying rates but at different final moisture content. Also if paper is dried at different relative humidities, it may result in different strength and optical properties.
Appendix A

Centrifuge Head and Centrifuge Cup Assembly for WRV Determination
Figure 30. Centrifuge Head and Centrifuge Cup Assembly for WRV Determination (69).
Appendix B

Sinclair Float-Washer Apparatus
Figure 31. Sinclair Float Washer Apparatus.
REFERENCES


