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The Optimization of a Recycled Thermomechanical Paper Using Fractionation

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THE OPTIMIZATION OF A RECYCLED THERMOMECHANICAL PAPER USING FRACTIONATION

BY

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ABSTRACT

The initial recycling of thermomechanical pulp leads to the flattening and increased flexibility of the fibers. Further recycling of the pulp leads to the unraveling of the fibers. The treatment of the fibers increases the bond potential of fibers while it decreases the fiber strength. Recycling of the fibers also leads to shortening of the fibers. The overall effect of recycling is the degradation of the finished product.

By varying the short fiber ratio the papers strength, physical, and optical properties can be directly affected. The strength properties dependent on bond potential are increased by adding short fiber and recycling. Strength properties dependent on the fiber strength are inversely affected, therefore decreased. The exception being the Z-direction strength properties which are slightly increased with short fiber addition. Physical properties, such as density and porosity, are increased as the fibers are recycled and short fiber is added. Varying the fiber ratios can not offset the effects of recycling on the optical properties. Overall, fractionation can be utilized to duplicate virgin paper in terms of strength and physical properties.

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CHAPTER I

INTRODUCTION

Secondary fiber is defined as any fibrous material that has undergone a manufacturing process and is being recycled as the raw material for another manufactured process. Recycled fibers generally have lower strength and create several problems with drainage when compared to virgin fibers. The mechanical properties of fibers as well their ability to swell are diminished after they are exposed to the pulping and drying conditions imposed during the papermaking cycle.[1]

Secondary fiber presents a threefold opportunity to the paper industry. The first opportunity is to make money, since the fiber can be obtained more cheaply and with less capital cost than virgin fiber. Secondly, it gives industry and the individual the opportunity to learn. This ever-changing resource requires continued updating of the technology necessary to handle the changing types of contaminants in order to produce a pulp well suited for papermaking and for the product desired. Last, but not least, it can provide the opportunity for a giant headache for the process engineer. To date, economics has driven this commitment.[2]

Recycling for the most part is not a new technology. The first commercial proposition was in 1800 when Matthias Koops established the Neckinger Mill in the

United Kingdom. The low point for the use of waste paper as a fiber source was in 1968 when it only represented 19.5% of the total sources. Since this time, waste paper recovery rates have steadily increased through the eighties and are projected to continue to do so through the turn of the century (Figure 1). Paper recycling offers the unusual benefits of being both economically and environmentally beneficial. Another incentive for recycling is the availability of virgin fiber resources. As forest area per person is being decreased, the importance of recovery fiber is becoming more prominent.[2]

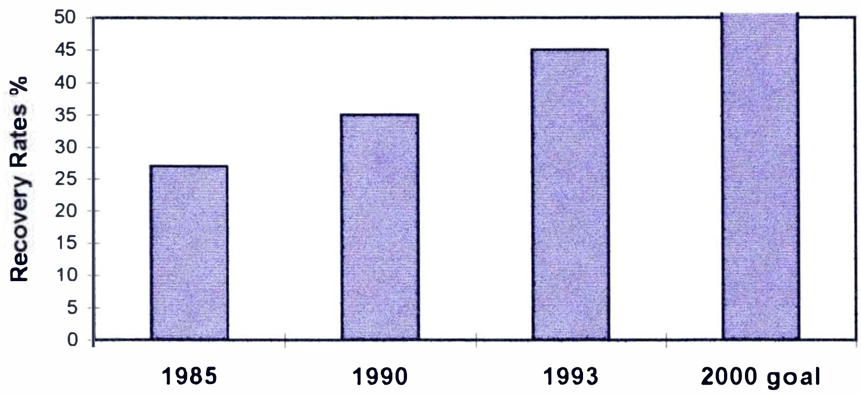


Figure 1: U.S. Paper Recover Rates [2]

Annual consumption of recycled fiber has been predicted to grow at a rate of 3-4% per year, from 20.5 million tons in 1989 to 28 million tons per year by the year 2000. Recycling is becoming more prominent in every grade of paper, from newsprint to fine writing grades. Environmental pressure along with legislation is also becoming a driving force for the recycle market. Several efforts are being made to require up to 40% of the 16 million tons per year of newsprint be made from recycled fiber.[2]

Recycling effects on chemical pulps have been well documented. Until recently, there has been little work done with mechanical pulps and the effects of recycling. Of the work done with mechanical pulps, even fewer people have focused on thermomechanical pulps (TMP) and the recycling effects. The use of TMP pulps is employed in several newsprint and board operations were the recycling effort is being focused. Hence, its seems very important to investigate the effects of recycling on TMP pulps along with ways of using these effects to the industries benefit.[1]

CHAPTER II

LITERATURE REVIEW

Recycled fibers are mainly influenced by the characteristics of the original pulping and paper making systems. The properties are further subject to variations from alternative pulping processes given to a specific choice or blend of wood species. Furthermore, fiber recovered from waste paper is incorporated in numerous grades of paper which again become part of the waste paper source. Waste paper also contains a multitude of contaminants, noncellulosic materials, which constitute up to 50% of its overall weight. The various additives, chemicals, and materials that are placed in or on the paper during manufacture or applied to paper products in converting and other manufacturing operations to enhance its specific user purpose, become the major contaminants in recycling.[1]

General Effects of Recycling

A considerable amount of research has been devoted to what is considered the fundamental problem of recycling, i.e. how fibers are affected by recycling procedures, and what resulting effects are seen in paper made from those fibers. Investigations into the effects of recycling have been many and varied. Furnish ranges from chemical, both bleached and unbleached, to mechanical pulps, including blends, have been studied.

Several recycling procedures on the laboratory and mill level have been performed in various forms and procedures to study the general effects of recycling.

It is generally accepted that the greatest change in any property of a pulp or paper occurs within the first recycle. This change is generally seen as a decrease in strength in chemical pulps and a slight increase in mechanical pulps. After the first recycle, the properties follow the same trends until the fourth recycle at which time the effects are slowed until the tenth recycle. The loss of strength in chemical pulps is attributed to the loss of bonding potential during recycling (Figure 2-1). This in return is attributed to the shortening and hornification, the irreversible loss of fiber swelling, of fibers. The difference between chemical and mechanical pulps when recycled is that mechanical fibers become flatter and more flexible. This allows for the increase in strength properties related to bonding potential (Figure 2-2).[3]

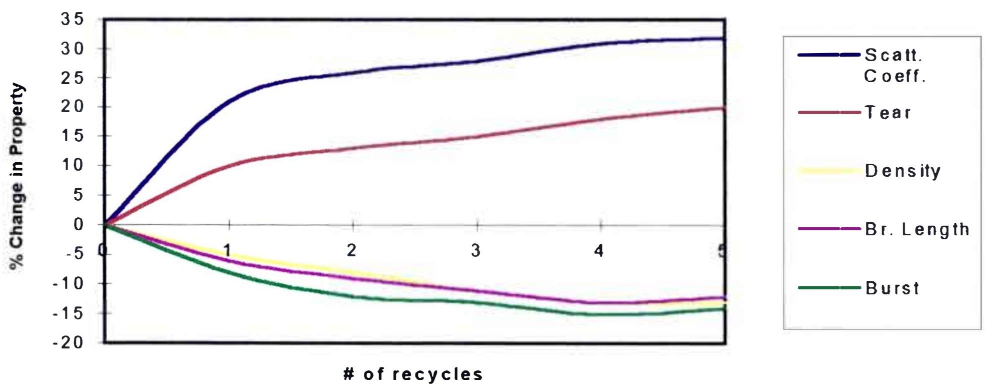


Figure 2-1: Recycling effects on chemical pulp [3]

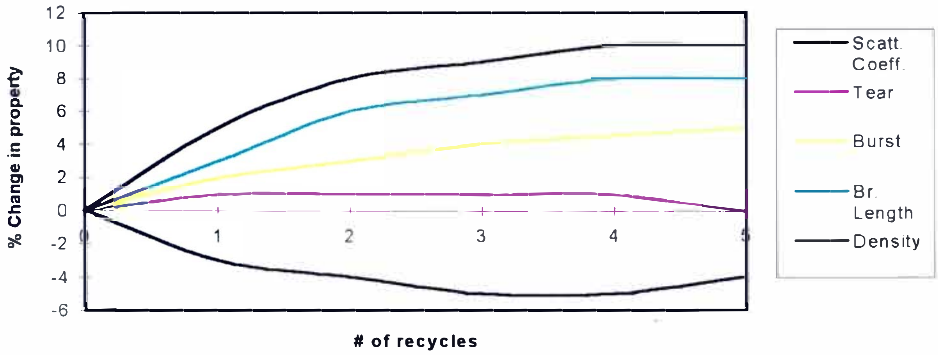


Figure 2-2: Recycling effects on mechanical pulps [3]

As the mechanical pulp fiber becomes more flexible it is able to conform to other fibers which in return allows for more bonds to be formed between fibers. The flattening of the fibers also leads to an increase in the total bonding area of a given fiber. This increase is seen as an increase in the bonding potential of the given fiber. Several of the strength properties are dependent on the bond strength as well as the fiber strength. This is reflected in the slight increases in these strength properties.[3]

Thermomechanical Pulp

Thermomechanical pulping (TMP) is a modification of standard refiner mechanical pulping (RMP), and is widely employed in high-tear pulps for newsprint and board. The modification comes from the addition of high pressure steam into the raw material, for a short period of time, during refining. The steaming serves to soften the chips, with the result that the pulp has a greater percentage of long fibers and fewer shives than that of traditional RMP. These longer fibers provide for a stronger pulp than either RMP or stoneground pulp (Table 2-1).[4]

Table 2-1: Comparison of Mechanical Pulps

	SGW	RMP	TMP
Energy Required, mJ/kg	5.0	6.4	7.0
Burst Index, $kPam^2/g$	1.4	1.9	2.3
Tear Index, mNm^2/g	4.1	7.5	9.0
Bulk, cm^3/g	2.5	2.9	2.7
Fiber Length, R-48	28	50	55
Shive Content, %	3.0	2.0	0.5
Brightness, %	61.5	59	58.5

Thermomechanical pulping has not gained extreme popularity industry wide as the result of three process variables. The first, energy consumption of the process is high when compared to other refining methods. Greater energy consumption is the result of the development of the fibers by breaking up the primary wall and peeling the S_1 layer. The second process variable is the thermal darkening of the pulp. This can be prevented but requires a greater energy consumption. The third variable is that the process most be carried out within a narrow temperature range. The ideal temperature occurs between 120 and 130°C. This temperature range allows for low energy separation of the fibers due to the softening of the lignin. Above the range results in over softening of the lignin which coats the fibers. Upon cooling the lignin turns to a glassy state which prevents fibrillation. For these reasons temperature most be closely monitored during the process.[4]

Principle of Fractionation

Fractionation works on a basic principle. Pulpstreams are subjected to different screen sizes to allow fibers to be separated by their size. The screens are placed in succession with each successive screen retaining a shorter fiber than the previous screen.

Screen sizes are determined by the desired end use of each pulp stream. Several mills utilize fractionation on a limited basis. The majority are board mills which separate the fibers on the basis of the longer, stronger fibers begin utilized for the liner board and the shorter fiber being used in the board median layer, center portion.[5,6,9]

Fiber Classification

There is no set industry standard for what classifies a fiber as short or long. It is generally accepted practice to use a given mesh screen, usually between 60 and 140, and use the determination that fiber passing through the screen is considered a short fiber and that remaining on top is the long fiber. Every article, discussing fractionation, offered a different view on the proper screen mesh. Table 2-2 represents various screen openings used in industry.[7,8]

Table 2-2: Screen Openings

Tyler series	Opening, mm	U.S. standard
10	1.68	12
12	1.41	14
14	1.19	16
20	0.841	20
28	0.595	30
35	0.420	40
48	0.297	50
65	0.210	70
100	0.149	100
150	0.105	140
200	0.074	200

Overview

On reviewing the publications reporting on the physical properties resulting from mechanical pulps, most are focused on the effects of including the recycled pulp into the regular production than on the recycling process itself. Several publications focus on the effects of recycling on pulp and paper. However, very few people have examined the recycling effects on TMP pulps despite their widespread use in the popular recycling grades of paper.

The question which arises when viewing the previous work is: what is being done to try and counter act the effects of recycling and to what extent does the shortening of the fibers have on the final product? Based on the above observations, there is enough demand and need to investigate the possibility of developing a process that would allow a recycled paper to simulate that of a virgin paper. Also, is the degradation of recycled TMP paper the result of the loss of bond potential or the shortening of fibers.

CHAPTER III

STATEMENT OF THE PROBLEM

Recycling is becoming the predominant process used for newsprint. Traditionally, newsprint was made from a mixture of stone-groundwood and chemical pulps. Over the last 20 years, this has been replaced by thermomechanical pulp (TMP) or chemi-thermomechanical pulp (CTMP) and most of the chemical pulps have been replaced.[2]

It is generally accepted that using recycled fiber will result in an overall lower quality of final product. In the case of mechanical pulp, it is the result of the “cutting” action occurring on the fibers. This cutting action produces a larger fraction of short fibers each time the fibers are recycled.[1]

Most mills have considered using fractionation as a means of counter-acting the recycling effects. None of the researchers have considered examining different long to short fiber ratios as a means of achieving optimum values for given properties. The majority of fractionation systems are employed in board mills. This allows for long fiber to be utilized in the liner and the short fibers to used in the median. The knowledge of how paper, of all varieties, is affected by different fiber ratios would allow recycled fiber to be effectively utilized.[10]

CHAPTER IV

OBJECTIVES OF THIS STUDY

The eight properties of paper and fiber considered in this study are tensile index, tear index, burst index, scattering coefficient, air resistance, opacity, brightness, and zero-span strength. The objectives are:

1.) To determine the general effects of recycling on the papers strength, physical, and optical properties.

2.) To evaluate the effects of fiber length on the strength, physical, and optical properties of paper.

3.) To compare the paper made from different fiber ratios i.e. short to long fiber ratios.

4.) To determine the feasibility of using fractionation as a means of matching the quality of a virgin paper with recycled fibers.

CHAPTER V

EXPERIMENTAL DESIGN AND METHODOLOGY

Experimental Design

A never-dried softwood thermomechanical pulp was used in the experiments. Initially, a sufficiently large number of handsheets were prepared so that handsheets could be used for testing handsheet properties and disintegrated for subsequent recycles. The redisintegrated pulp was used to prepare handsheets for each subsequent recycle. This process was carried out over four recycles. The technique involved repeated sheet making, drying, slushing, refining, and fractionation. Experiments were conducted to measure the effects of short fiber ratio on recycled paper when compared to that of virgin paper. Rebeating was performed to maintain a freeness to duplicate sheet making conditions for each recycle. The schematic for the experiment is shown in Figure 5-1.

Experimental Methods

Recycling Procedure

The recycling procedure involved a five step process which was duplicated over four recycles. They are as follows:

Step 1: The first step in the recycling process was to soak the control handsheets for two hours. This was done with 30 grams of oven-dried fiber in 2000 ml. of distilled water. The water temperature was held at 25°C to ensure each recycle could be carried out under the same conditions. For the each successive recycle the previous recycle was soaked and the above procedure was followed.

Step 2: The second step in the process was to disintegrate each 30 gram sample in the British disintegrator. The disintegrator was ran for two minute intervals for each sample. After disintegration the pulp was at 1.5% consistency.

Step 3: The third step involved the actual refining of the pulp to a given freeness using the PFI mill located in Western Michigan Universities' wet lab. Before refining the pulp samples from the disintegrator had to be dewatered to increase the consistency to 4%, this is the Tappi standard operating conditions. The samples were then ran in the PFI mill according to a beating curve to maintain a freeness of approxiametly 200.

Step 4: The fourth step involved the fractionation of the recycled pulp. This was carried out using an industry standard 100 mesh screen. The 100 mesh screen contains openings of 0.148 millimeters (see table 2-2). The fiber remaining on the screen was separated from that passing through and classified as the long fiber ratio. During screening agitation was maintained in the pulp slurry to help prevent flocculation of the fibers. The pulp slurry utilized before screening was reduced to approxiametly 0.4% consistency to allow for proper screening.[8]

Step 5: The fifth step was the actual formation of handsheets. Four short to long fiber ratios were decided on: 10/90, 20/80, 30/70, and 40/60. The ratios were mass based when mixing handsheet mixtures. A British Handsheet maker was utilized to form 2 gram handsheets of the various ratios. Sheets were subjected to pressing and then drying on a drum dryer held at 250°F. Several handsheets were formed for each ratio with the remaining long fiber pulp being made into 2 gram handsheets. The long fiber handsheets had to be formed because there was a larger quantity of long fibers than short fibers.

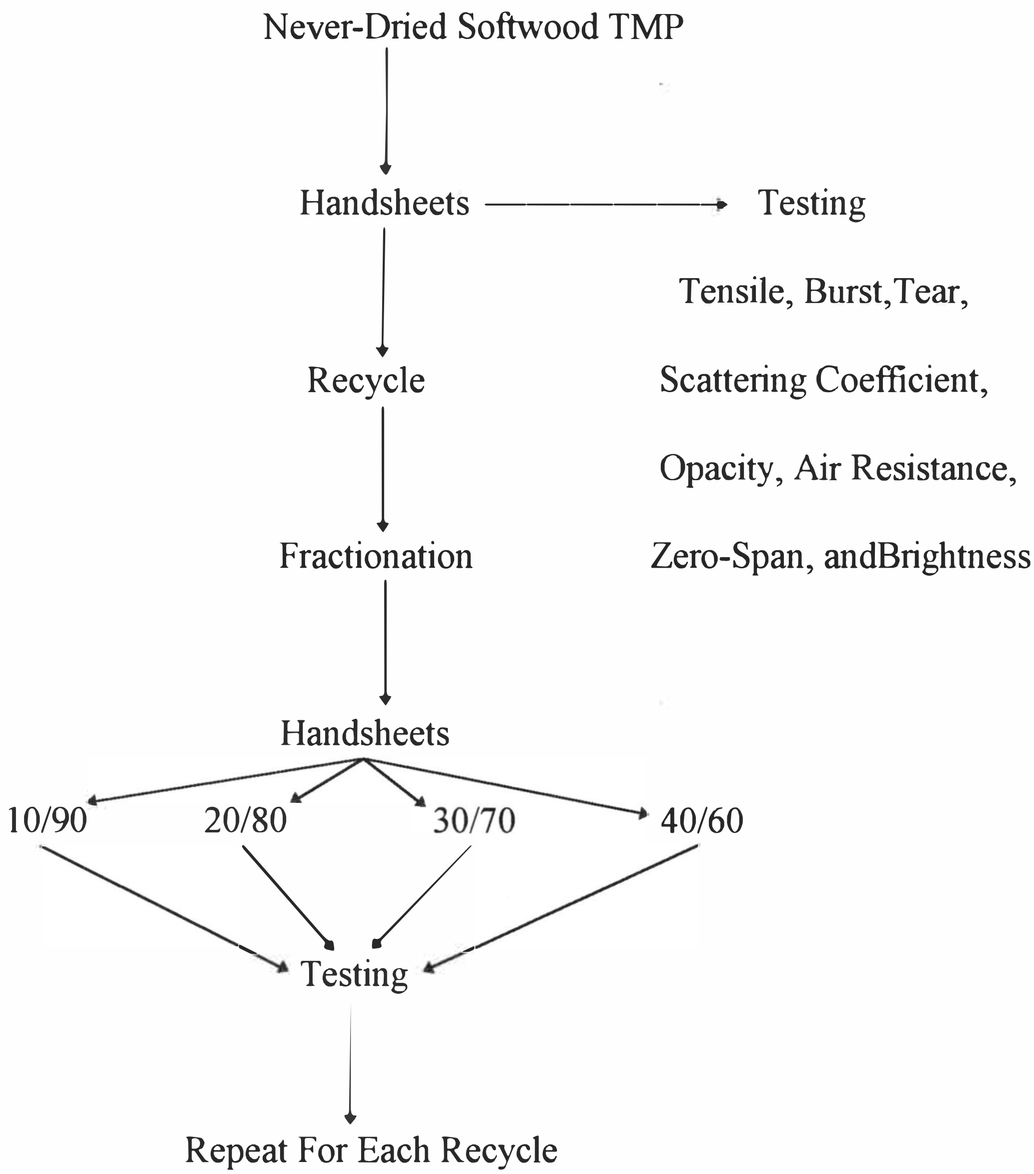
Handsheet Testing

The properties tested included the following: Tensile Strength, Tear Strength, Burst Strength, Scattering Coefficient, Air Resistance, Opacity, Brightness, and Zero-Span Strength. Testing was carried out in accordance with TAPPI test methods shown in Table 5-1.

Table 5-1: TAPPI Test Methods

Tensile Strength	T-494
Tear Strength	T-414
Burst Strength	T-403
Zero-Span Strength	T-231
Scattering Coefficient	T-425 om-91
Air Resistance	T-460 om-88
Opacity	T-425 om-86
Brightness	T-452 om-87

Figure 5-1: Experimental Schematic



CHAPTER VI

RESULTS

There is no evidence of other published results on variations of thermomechanical paper properties across short fiber fractions and recycling factors. Hence, these results cannot be compared with those of other experiments.

Experimental Data Analysis

The data presented for each ratio and its respective recycle is the average of test taken over five separate sheets. Standard deviations from the averages were calculated are also presented along with the values. This allowed a more accurate analysis of data when comparing recycles to that of the control sheet. All data representative of strength properties is in terms of indexes. The use of indexes allows for weight variations to be compensated for. Individual recycle results for handsheet properties are presented in Tables 6-1, 6-2, 6-3, and 6-4.

Screening Results

The entire experiment depended on the accuracy of separating long and short fibers during screening. Figure 6-1 represents the results of the screening process used in this experiment. Representative samples form the control, long fiber, and short fiber were collected on weight basis and ran in the Kajanni fiber length analyzer. The short fiber is representative of what passed through the 100 mesh screen.

Table 6-1: First Recycle Data

		Never-dried	First Recycle							
	units	**Control**	**10/90**	dev.	**20/80**	dev.	**30/70**	dev.	**40/60**	dev.
Basis Weight	g/m^2	111.56	115.23	2.72	110.96	2.80	113.04	4.28	111.61	2.67
Caliper	mils	12.20	11.96	0.16	11.36	0.12	11.29	0.21	11.16	0.09
Density	g/cm^3	0.38	0.38	N/A	0.38	N/A	0.40	N/A	0.40	N/A
Tear Force	mN	866.42	1061.05	32.65	878.98	87.90	897.81	81.65	866.42	60.27
Tear Index	mNm^2/g	7.77	9.21	0.26	8.49	0.69	7.94	0.69	7.76	0.66
Tensile Load	kg	6.36	6.93	0.68	6.49	0.34	6.40	1.05	6.16	3.14
Tensile B.L.	km	3.80	4.01	0.39	3.85	0.01	3.80	0.55	3.68	0.28
Tensile Index	Nm^2/g	37.27	39.32	1.12	37.76	0.06	37.19	1.86	36.08	1.01
Burst	psi	31.07	35.48	2.18	35.20	2.60	36.34	2.39	31.66	2.49
Burst Index	kPam^2/g	1.92	2.12	0.17	2.19	0.22	2.22	0.15	2.25	0.29
Zero-Span	psi	51.40	44.20	7.44	54.40	6.72	61.40	7.92	72.20	3.44
Air Resistance	sec/100ml	38.25	13.50	N/A	31.50	N/A	44.88	N/A	67.10	N/A
Opacity	%	98.99	99.65	N/A	98.70	N/A	98.64	N/A	97.95	N/A
Brightness	%	46.27	38.63	1.43	38.00	1.08	36.67	0.41	36.07	0.63
Scatt. Coeff.	m^2/kg	28.54	32.69	N/A	24.21	N/A	23.62	N/A	19.62	N/A

Table 6-2: Second Recycle Data

		Never-dried	Second Recycle							
	units	Control	10/90	dev.	20/80	dev.	30/70	dev.	40/60	dev.
Basis Weight	g/m^2	111.56	114.35	5.00	112.82	5.83	108.43	1.93	114.02	5.92
Caliper	mils	12.20	11.90	0.64	11.52	0.58	10.10	0.24	10.46	0.51
Density	g/cm^3	0.38	0.38	N/A	0.39	N/A	0.42	N/A	0.44	N/A
Tear Force	mN	866.42	1035.94	37.67	948.04	10.05	829.19	32.48	835.03	35.76
Tear Index	mNm^2/g	7.77	9.06	0.49	8.43	0.44	7.65	0.39	7.36	0.60
Tensile Load	kg	6.36	6.23	0.75	6.37	0.74	6.75	0.58	6.87	0.32
Tensile B.L.	km	3.80	3.64	0.42	3.75	0.32	4.14	0.29	4.04	0.38
Tensile Index	Nm^2/g	37.27	35.69	1.16	36.82	2.06	39.42	0.39	39.65	0.82
Burst	psi	31.07	29.54	0.95	36.66	0.95	33.56	2.54	37.22	2.70
Burst Index	kPam^2/g	1.92	1.79	0.48	2.21	0.06	2.19	0.16	2.25	0.14
Zero-Span	psi	51.40	37.40	4.72	37.00	5.20	52.60	4.72	62.00	2.00
Air Resistance	sec/100ml	38.25	17.60	N/A	30.90	N/A	52.25	N/A	72.75	N/A
Opacity	%	98.99	99.65	N/A	98.59	N/A	99.65	N/A	99.41	N/A
Brightness	%	46.27	36.67	0.71	35.98	0.62	35.14	0.89	33.92	2.62
Scatt. Coeff.	m^2/kg	28.54	32.38	N/A	28.67	N/A	27.10	N/A	27.34	N/A

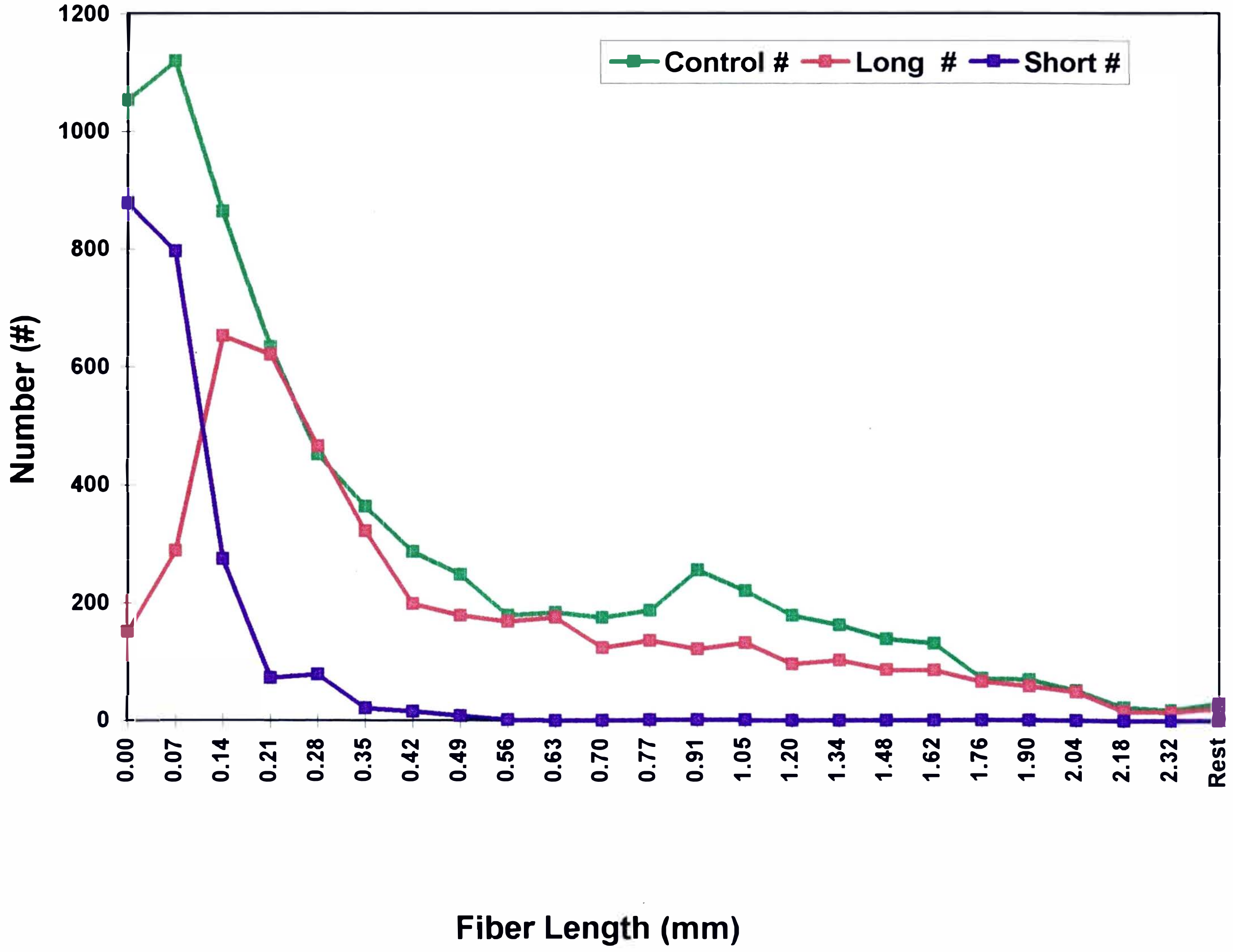
Table 6-3: Third Recycle Data

		Never-dried	Third Recycle							
	units	Control	10/90	dev.	20/80	dev.	30/70	dev.	40/60	dev.
Basis Weight	g/m^2	111.56	111.06	2.81	109.75	4.52	107.45	5.26	117.97	2.06
Caliper	mils	12.20	11.14	0.15	11.24	0.21	11.20	0.60	10.56	0.02
Density	g/cm^3	0.38	0.40	N/A	0.39	N/A	0.38	N/A	0.44	N/A
Tear Force	mN	866.42	784.80	25.11	929.20	52.74	822.47	45.21	784.80	62.78
Tear Index	mNm^2/g	7.77	7.07	0.28	8.51	0.69	7.70	0.62	6.65	0.47
Tensile Load	kg	6.36	5.97	0.48	5.92	0.55	5.73	0.62	6.86	0.49
Tensile B.L.	km	3.80	3.56	0.22	3.58	0.38	3.67	1.68	3.88	0.31
Tensile Index	Nm^2/g	37.27	34.93	0.26	35.09	2.29	36.18	1.13	38.08	1.38
Burst	psi	31.07	25.40	2.25	26.12	3.14	26.32	1.94	33.18	4.58
Burst Index	kPam^2/g	1.92	1.57	0.15	1.63	0.15	1.70	0.19	1.94	0.26
Zero-Span	psi	51.40	35.60	3.28	30.00	2.00	35.60	2.88	39.00	0.80
Air Resistance	sec/100ml	38.25	19.95	N/A	38.70	N/A	105.25	N/A	119.20	N/A
Opacity	%	98.99	99.67	N/A	99.36	N/A	98.15	N/A	99.38	N/A
Brightness	%	46.27	33.85	0.63	33.50	0.40	33.00	1.09	30.60	0.43
Scatt. Coeff.	m^2/kg	28.54	29.60	N/A	26.16	N/A	20.94	N/A	22.56	N/A

Table 6-4: Fourth Recycle Data

		Never-dried	Fourth Recycle							
	units	**Control**	**10/90**	dev.	**20/80**	dev.	**30/70**	dev.	**40/60**	dev.
Basis Weight	g/m^2	111.56	110.08	3.86	111.39	2.76	109.64	4.02	110.19	3.65
Caliper	mils	12.20	9.86	0.23	9.80	0.03	9.10	0.17	9.42	0.30
Density	g/cm^3	0.38	0.44	N/A	0.45	N/A	0.48	N/A	0.46	N/A
Tear Force	mN	866.42	640.40	48.66	564.39	17.40	618.03	29.43	654.00	61.04
Tear Index	mNm^2/g	7.77	6.23	1.76	6.02	0.33	5.73	0.12	5.92	0.33
Tensile Load	kg	6.36	6.17	0.14	6.26	0.64	5.77	0.37	5.71	0.33
Tensile B.L.	km	3.80	3.80	0.09	3.78	0.32	3.41	0.17	3.45	0.20
Tensile Index	Nm^2/g	37.27	37.30	0.88	37.07	2.01	34.39	1.10	33.87	1.97
Burst	psi	31.07	31.83	0.42	33.10	2.28	31.50	0.33	27.50	0.80
Burst Index	kPam^2/g	1.92	2.06	0.02	2.03	0.10	1.99	0.08	1.72	0.06
Zero-Span	psi	51.40	55.20	3.36	57.20	3.36	56.20	1.92	61.40	2.08
Air Resistance	sec/100ml	38.25	38.00	N/A	46.65	N/A	107.23	N/A	126.25	N/A
Opacity	%	98.99	99.88	N/A	99.89	N/A	99.50	N/A	98.64	N/A
Brightness	%	46.27	33.02	0.54	32.38	0.36	30.93	0.83	30.81	0.95
Scatt. Coeff.	m^2/kg	28.54	35.58	N/A	34.75	N/A	27.01	N/A	20.72	N/A

Figure 6-1: Screening Results in Terms of Fiber Length



TENSILE INDEX

Figure 6-2: Recycling Effects

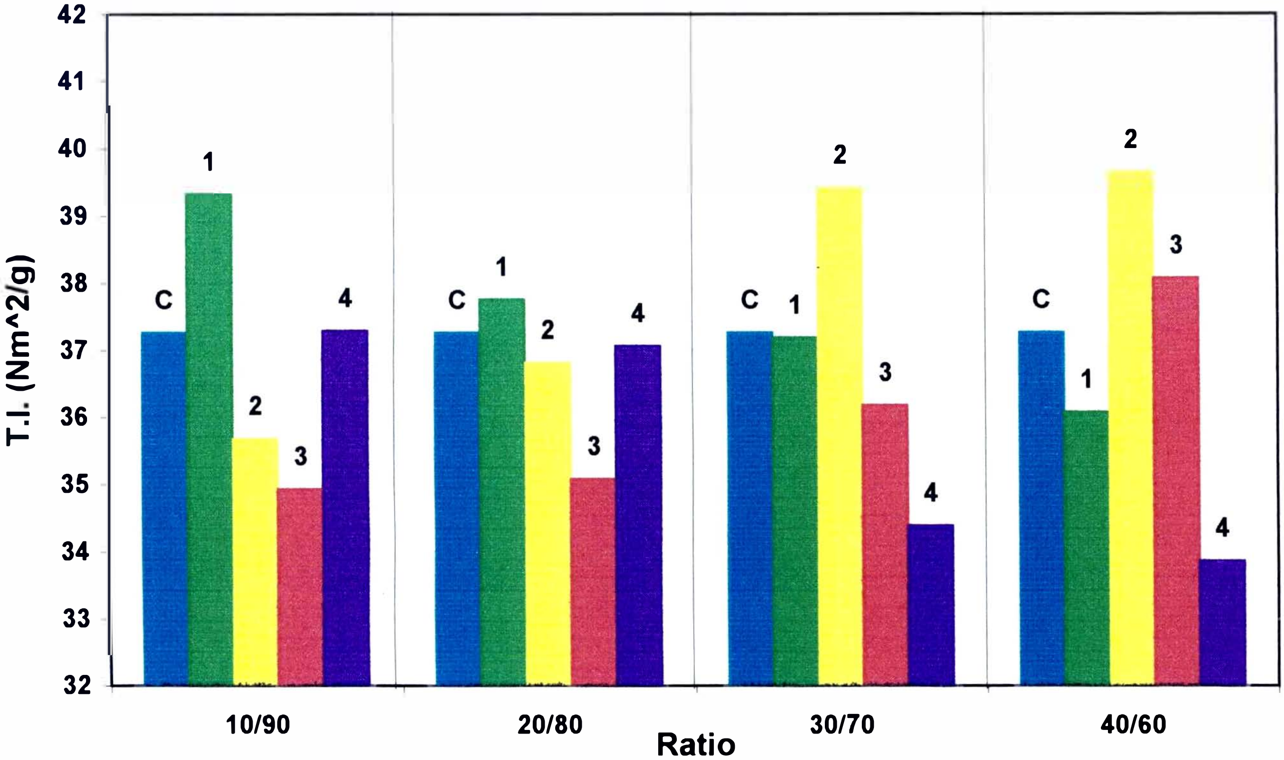
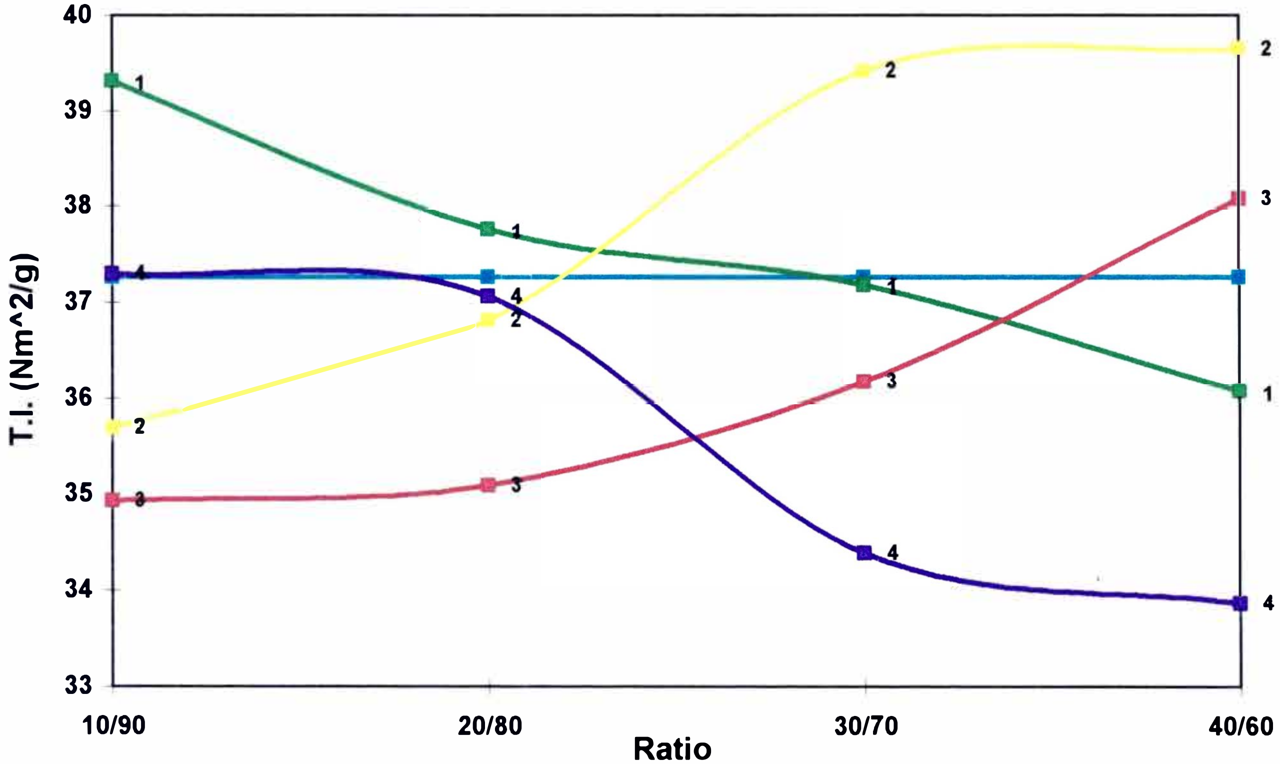


Figure 6-3: Fiber Ratio Effects



TEAR INDEX

Figure 6-4: Recycling Effects

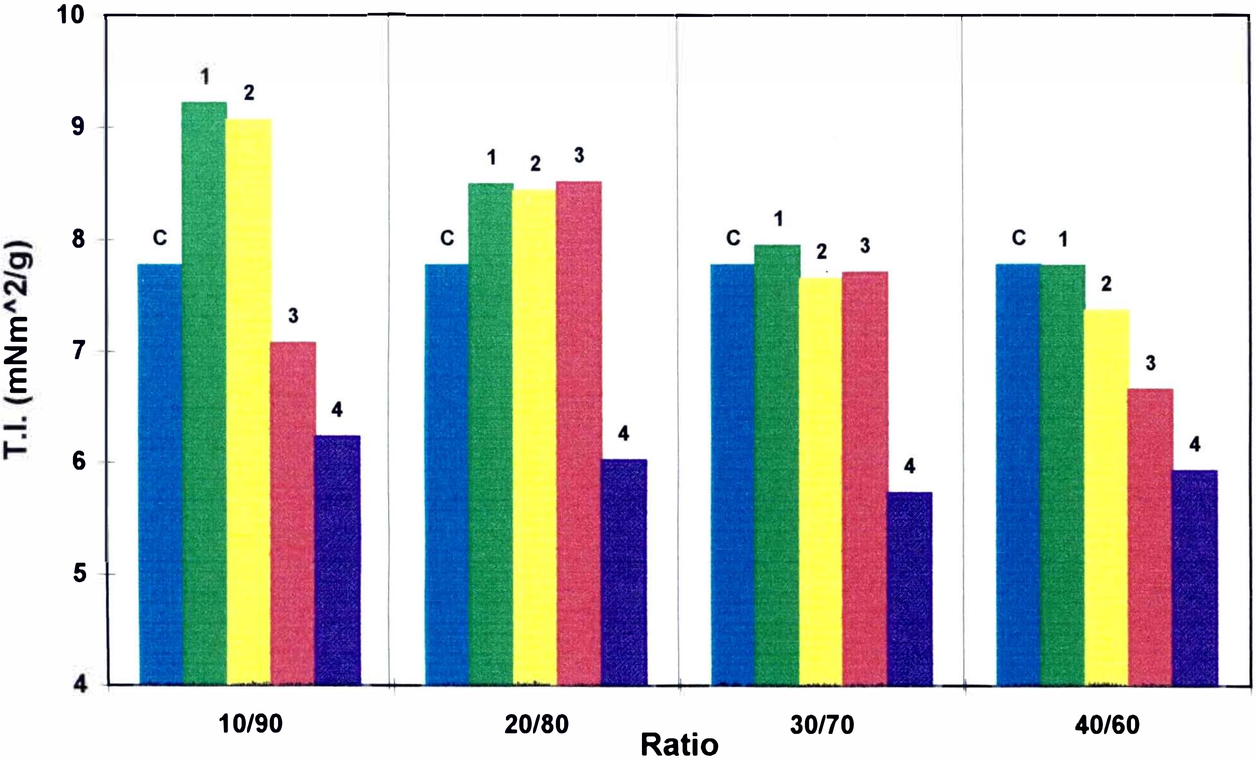
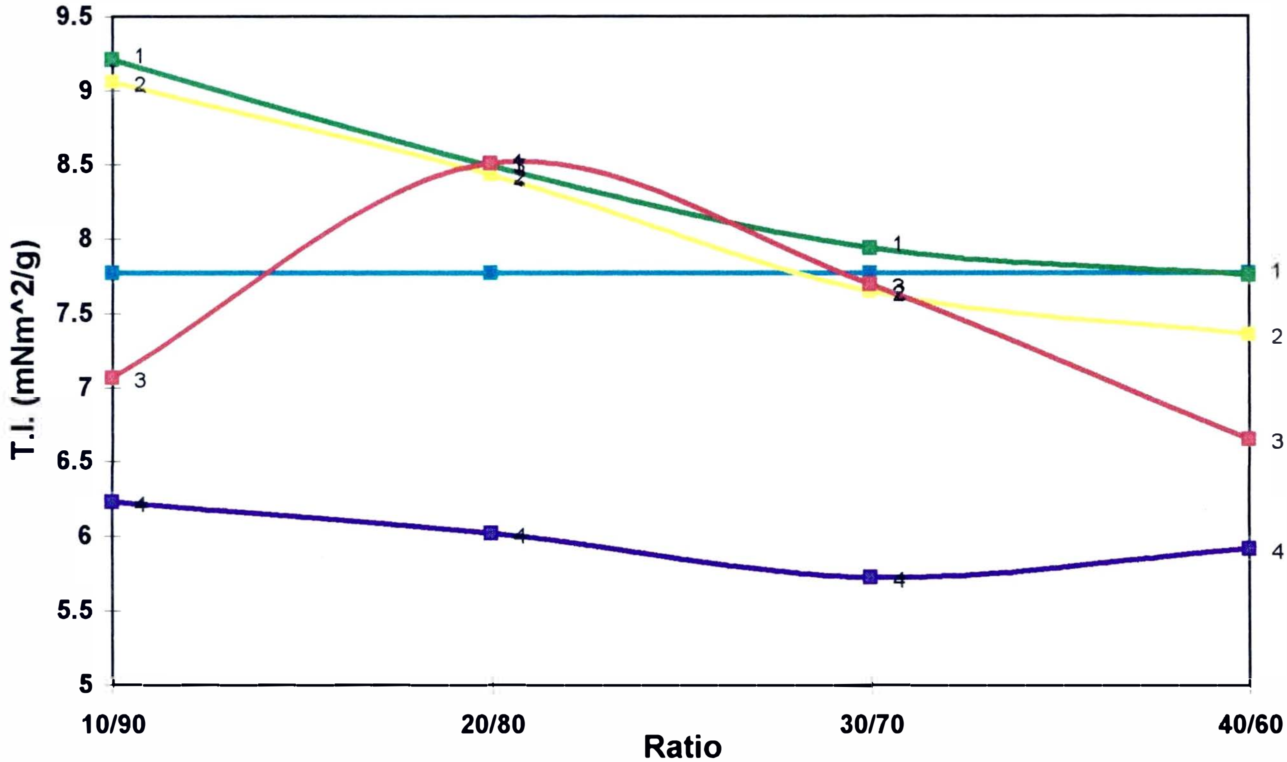


Figure 6-5: Fiber Ratio Effects



BURST INDEX

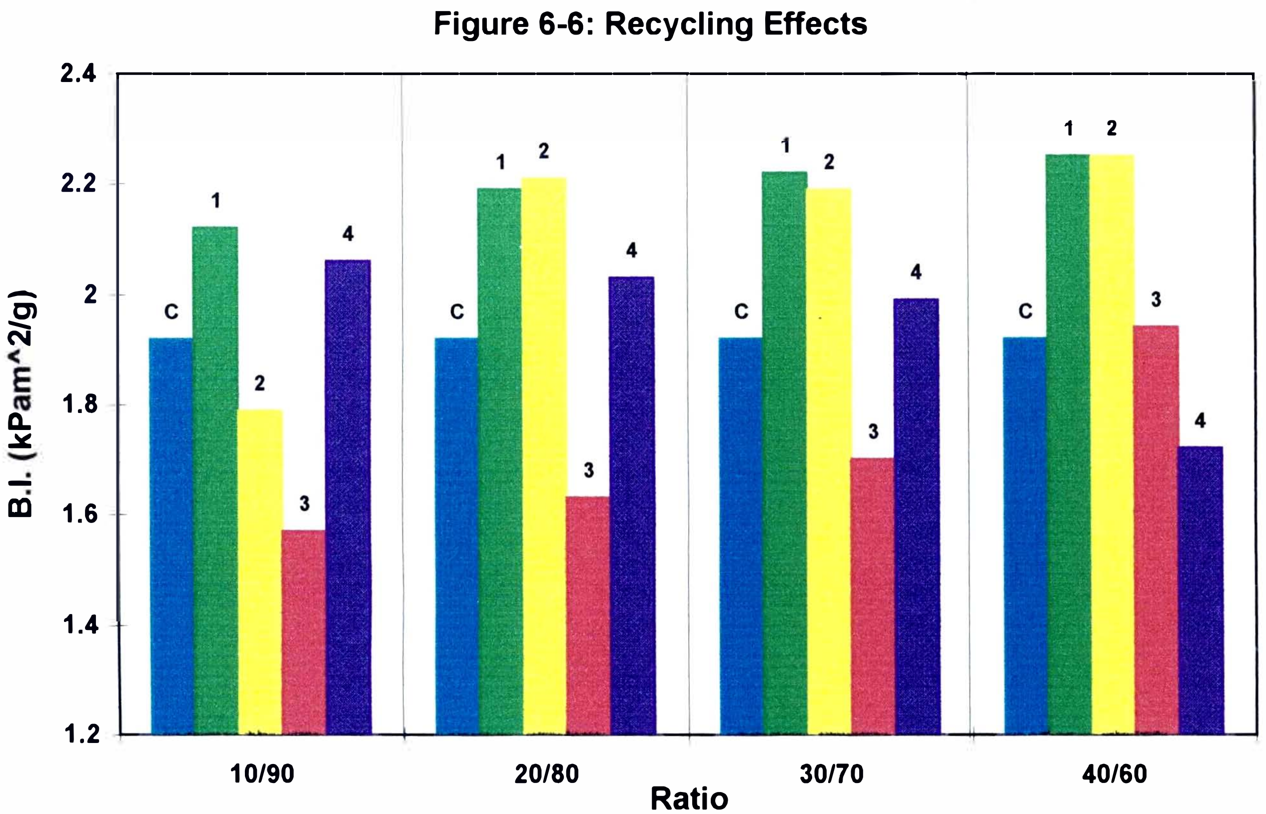


Figure 6-6: Recycling Effects
B.I. (kPam^2/g)
2.4
2.2
2
1.8
1.6
1.4
1.2
C
1
2
3
4
10/90
20/80
30/70
40/60
Ratio

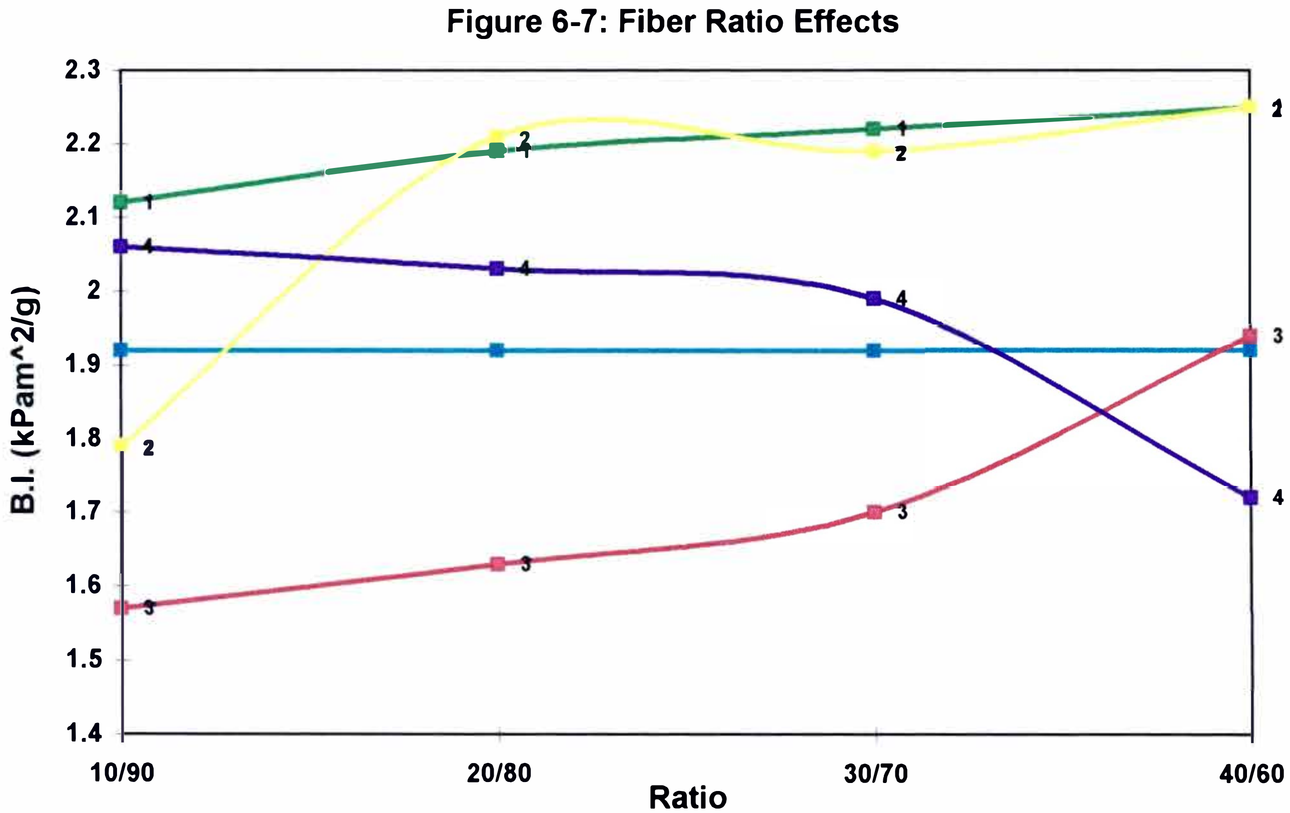


Figure 6-7: Fiber Ratio Effects
B.I. (kPam^2/g)
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1
2
3
4
10/90
20/80
30/70
40/60
Ratio

ZERO SPAN STRENGTH

Figure 6-8: Recycling Effects

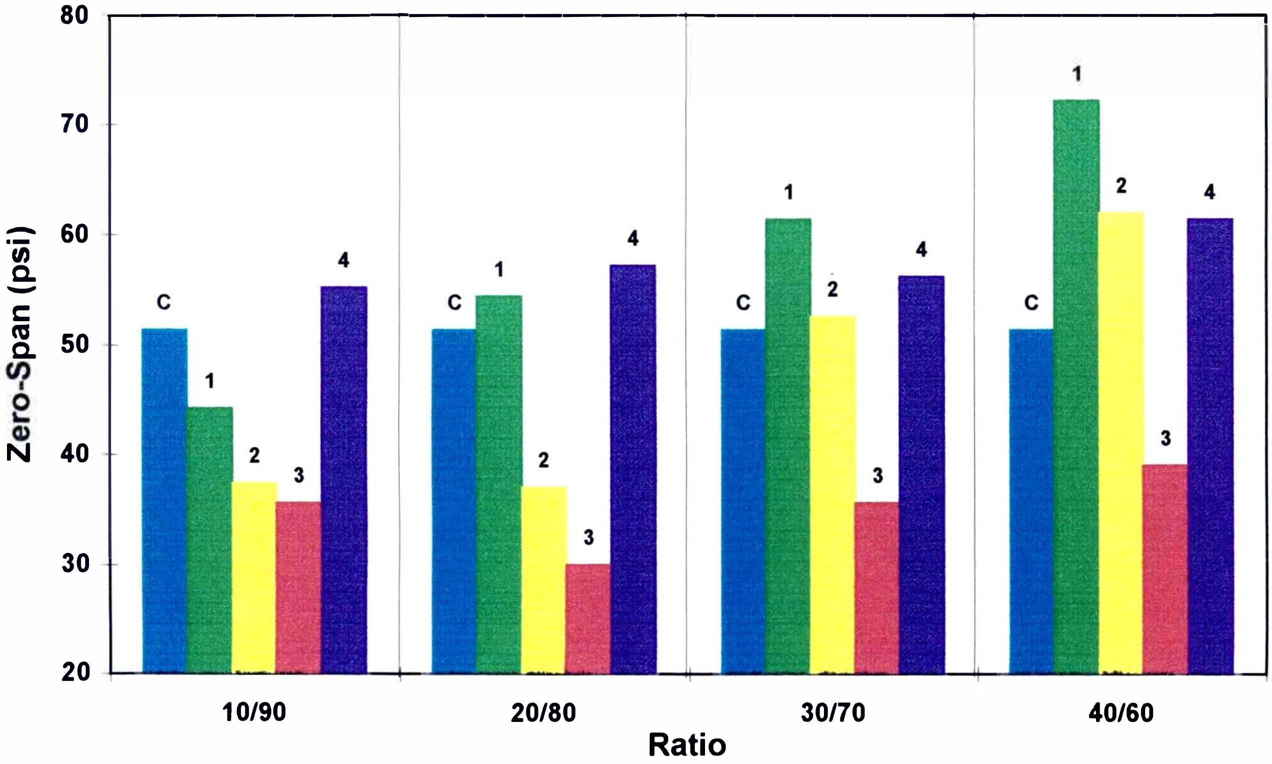
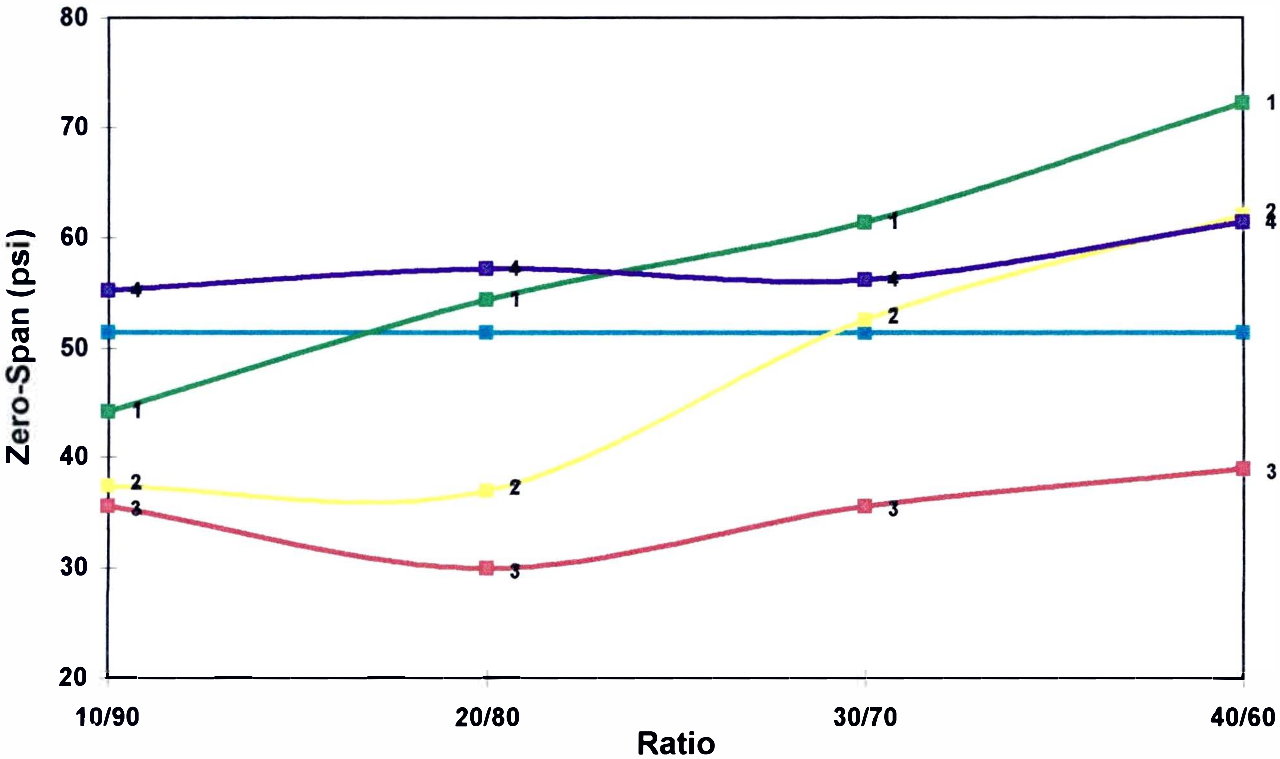


Figure 6-9: Fiber Ratio Effects



DENSITY

Figure 6-10: Recycling Effects

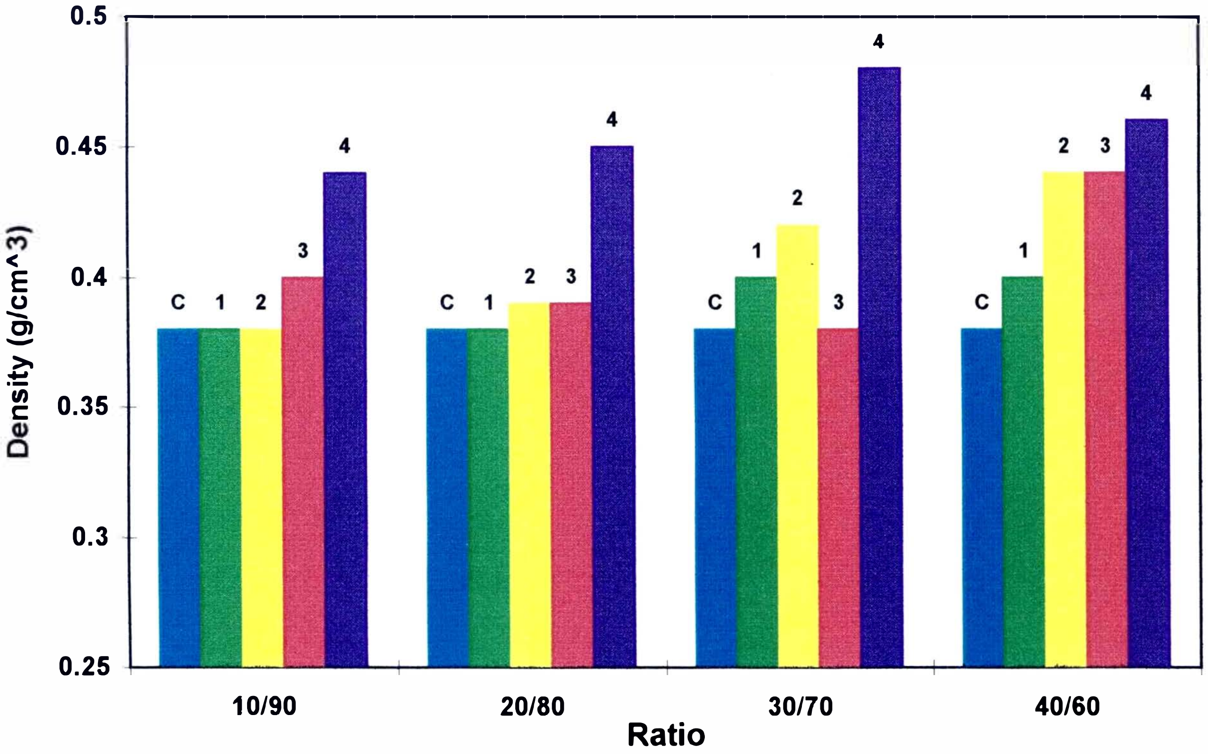
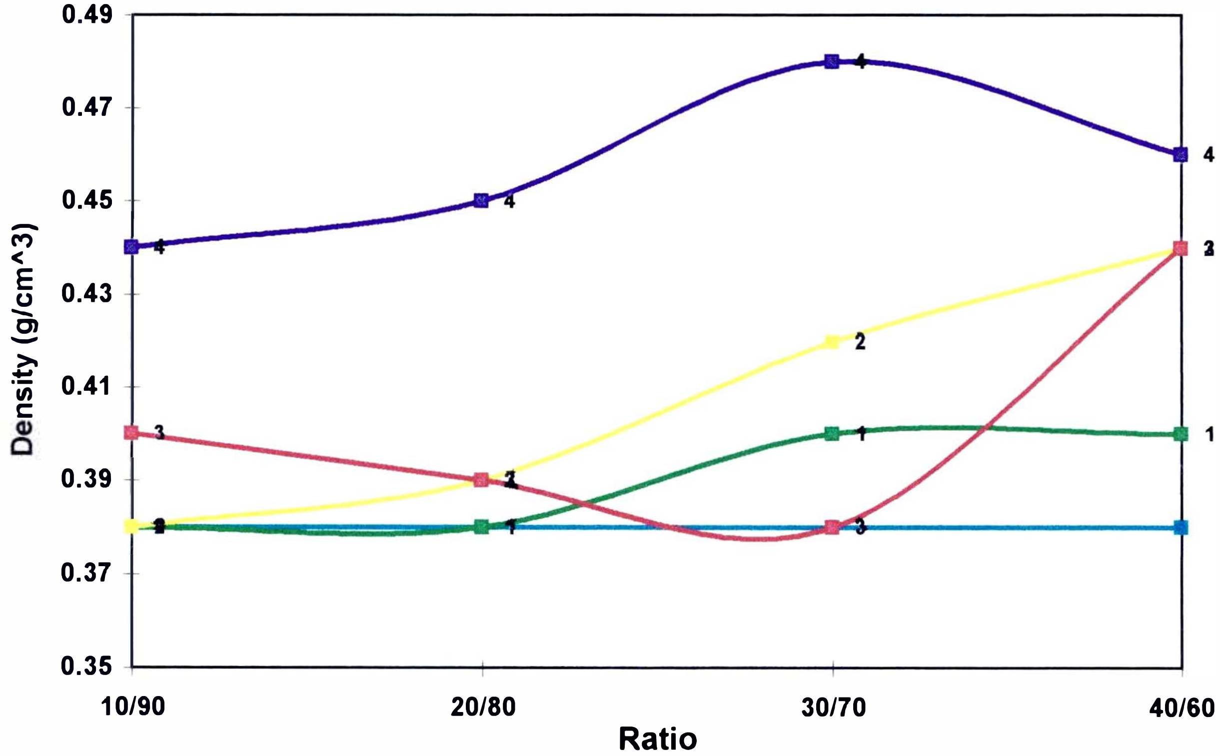


Figure 6-11: Fiber Ratio Effects



AIR RESISTANCE

Figure 6-12: Recycling Effects

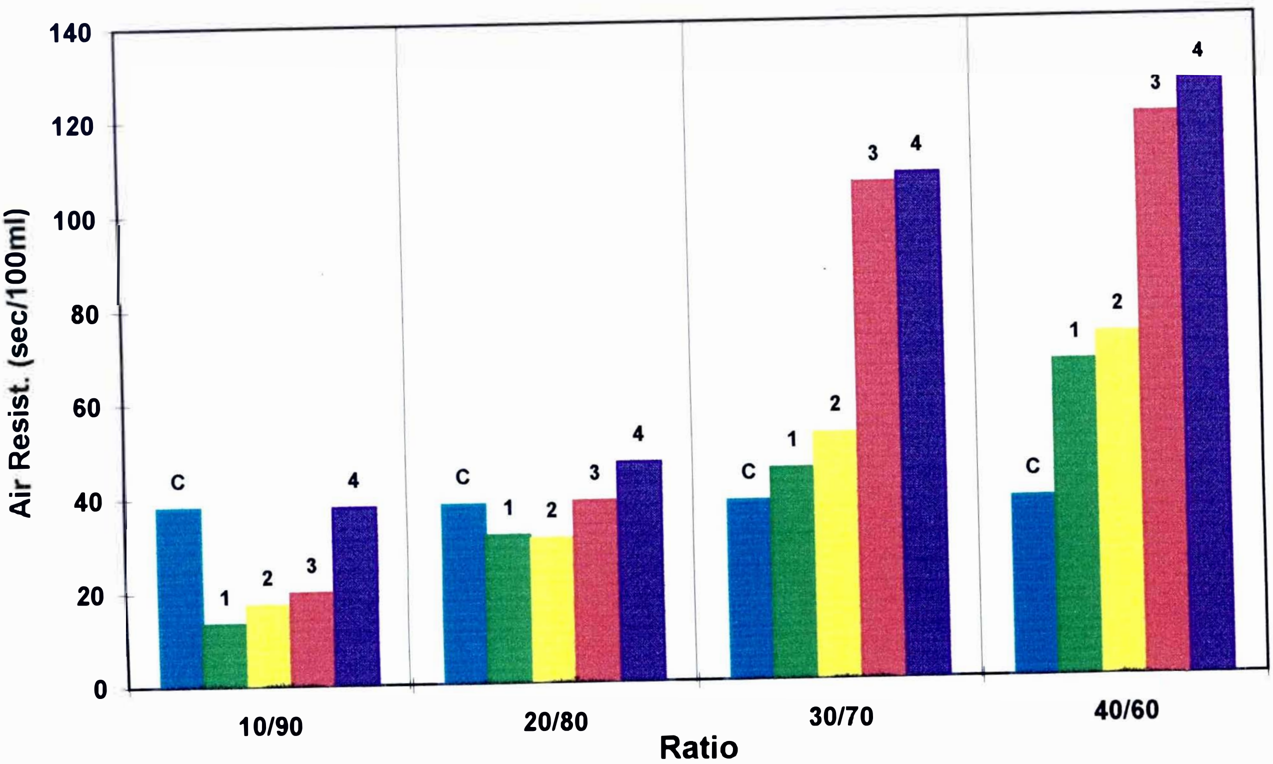
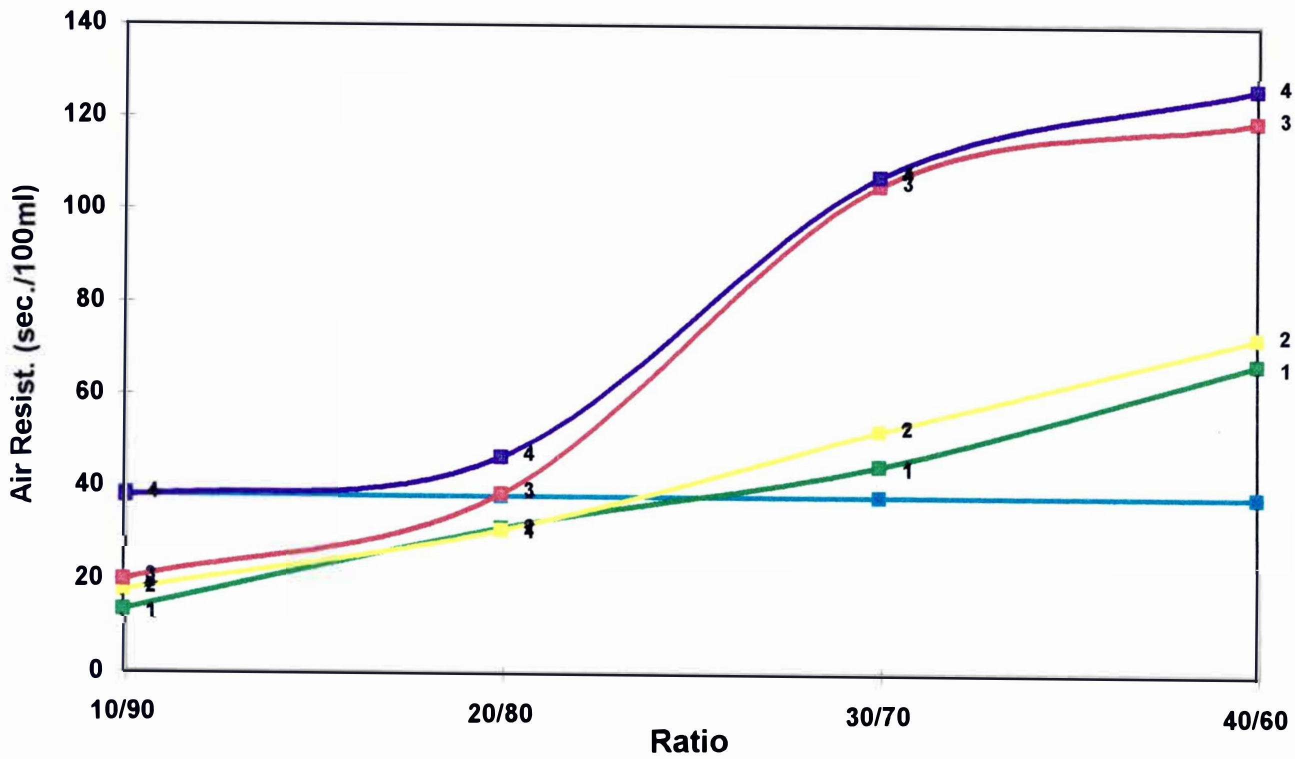


Figure 6-13: Fiber Ratio Effects



OPACITY

Figure 6-14: Recycling Effects

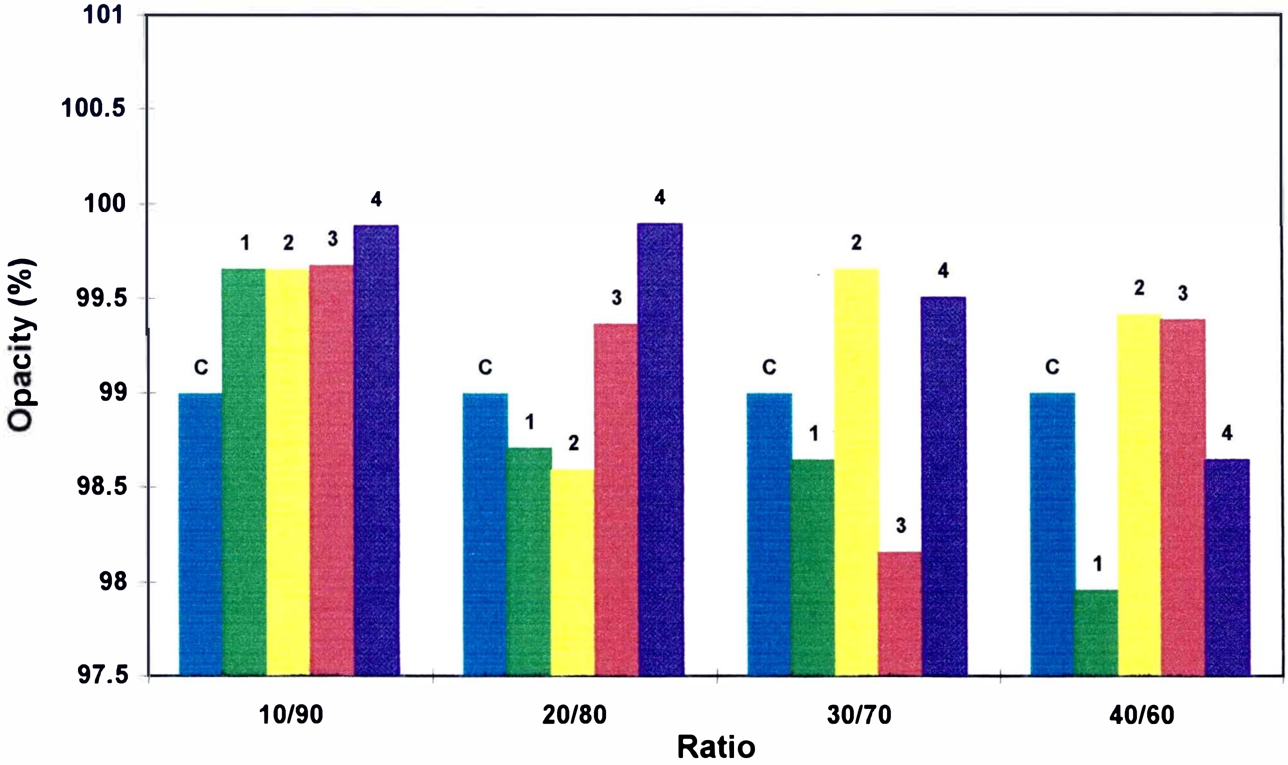
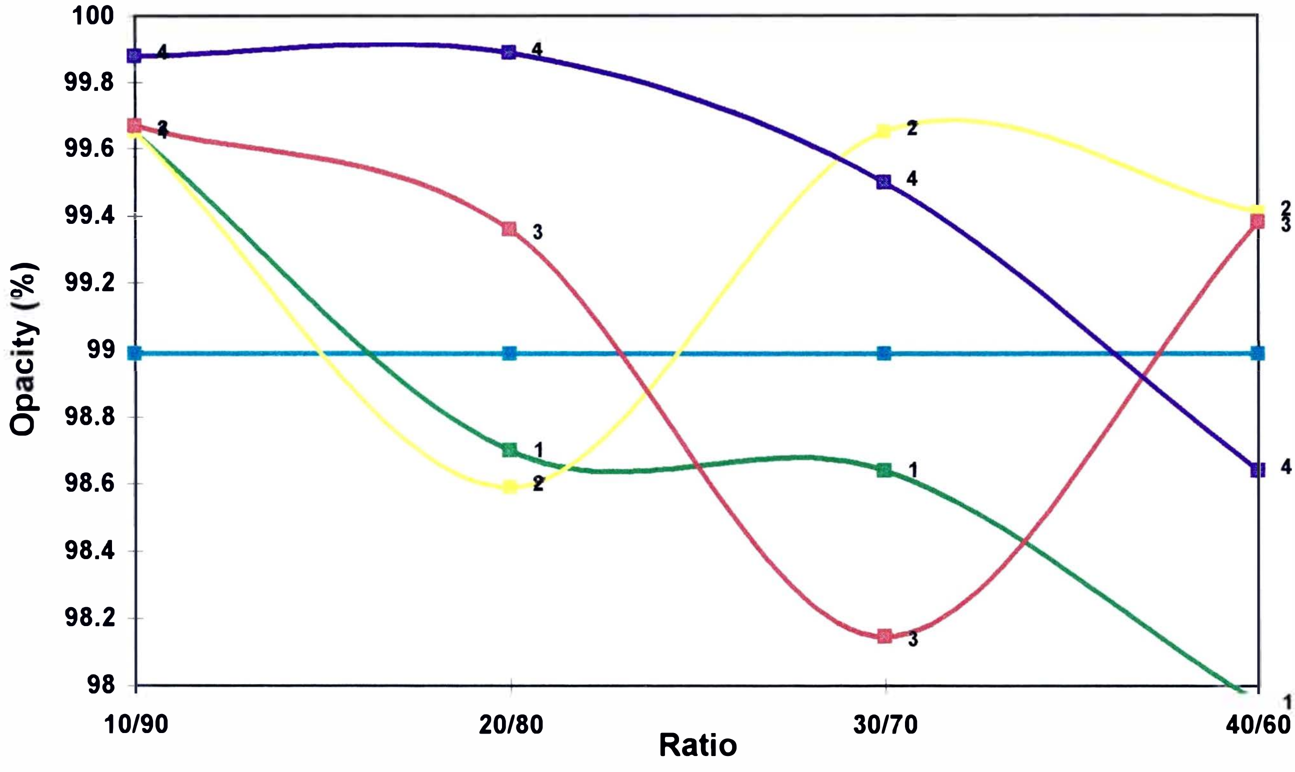


Figure 6-15: Fiber Ratio Effects



BRIGHTNESS

Figure 6-16: Recycling Effects

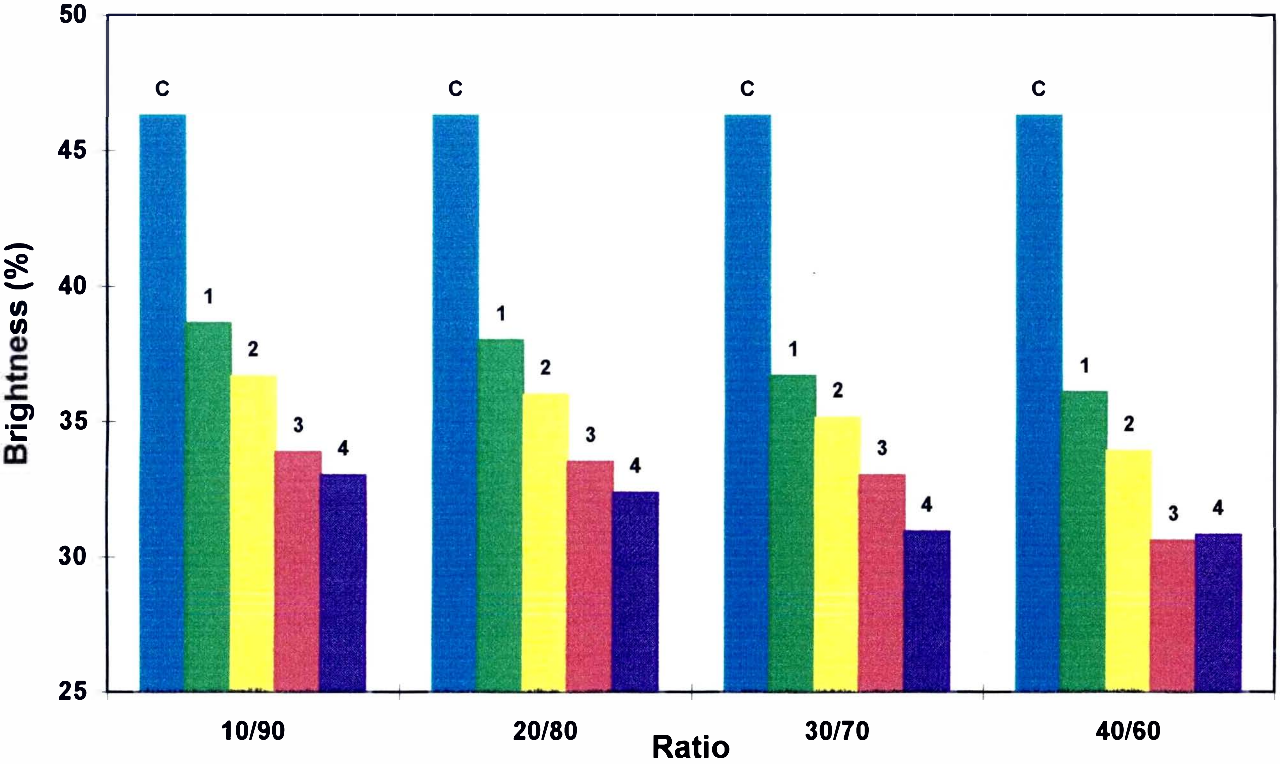
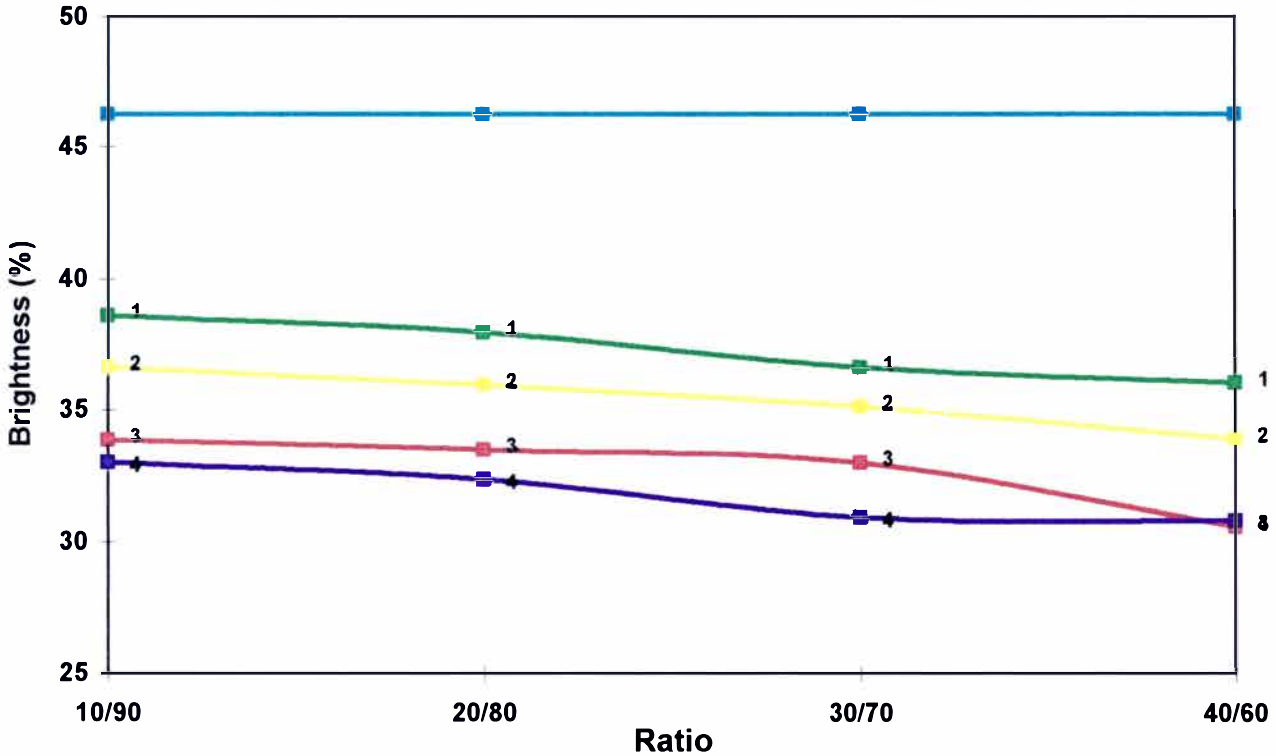


Figure 6-17: Fiber Ratio Effects



SCATTERING COEFICIENT

Figure 6-18: Recycling Effects

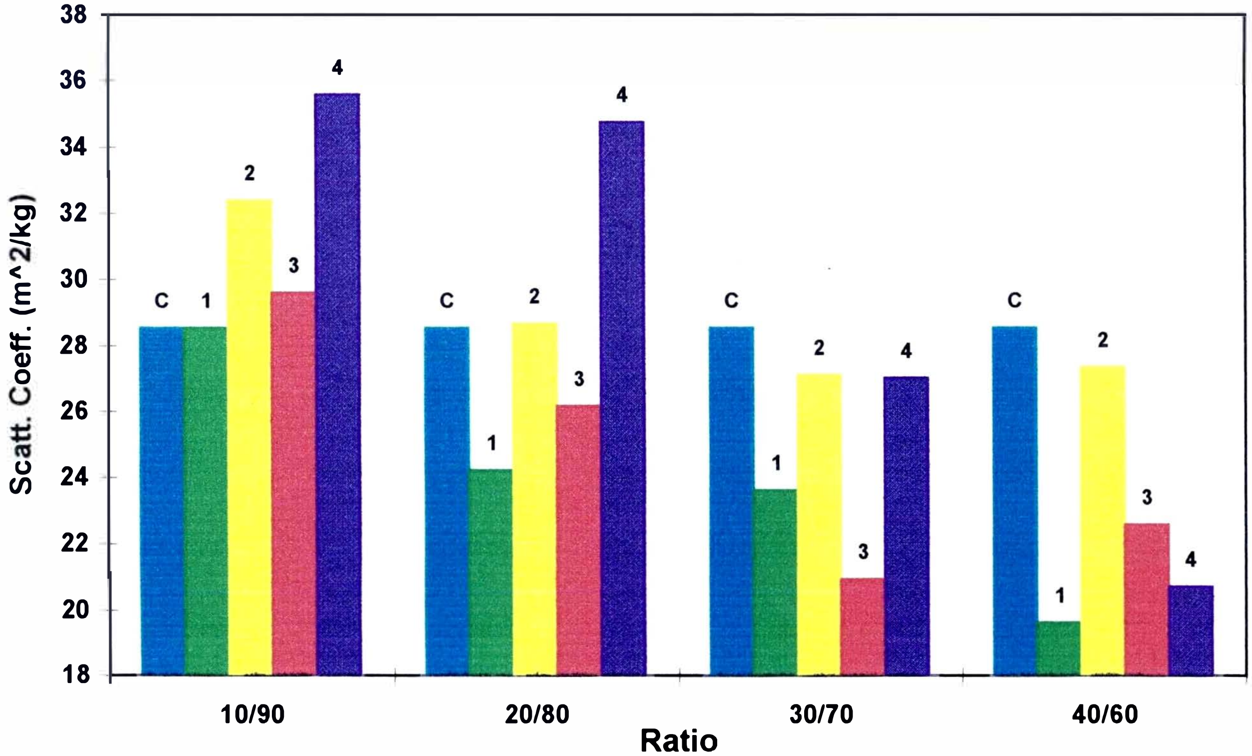
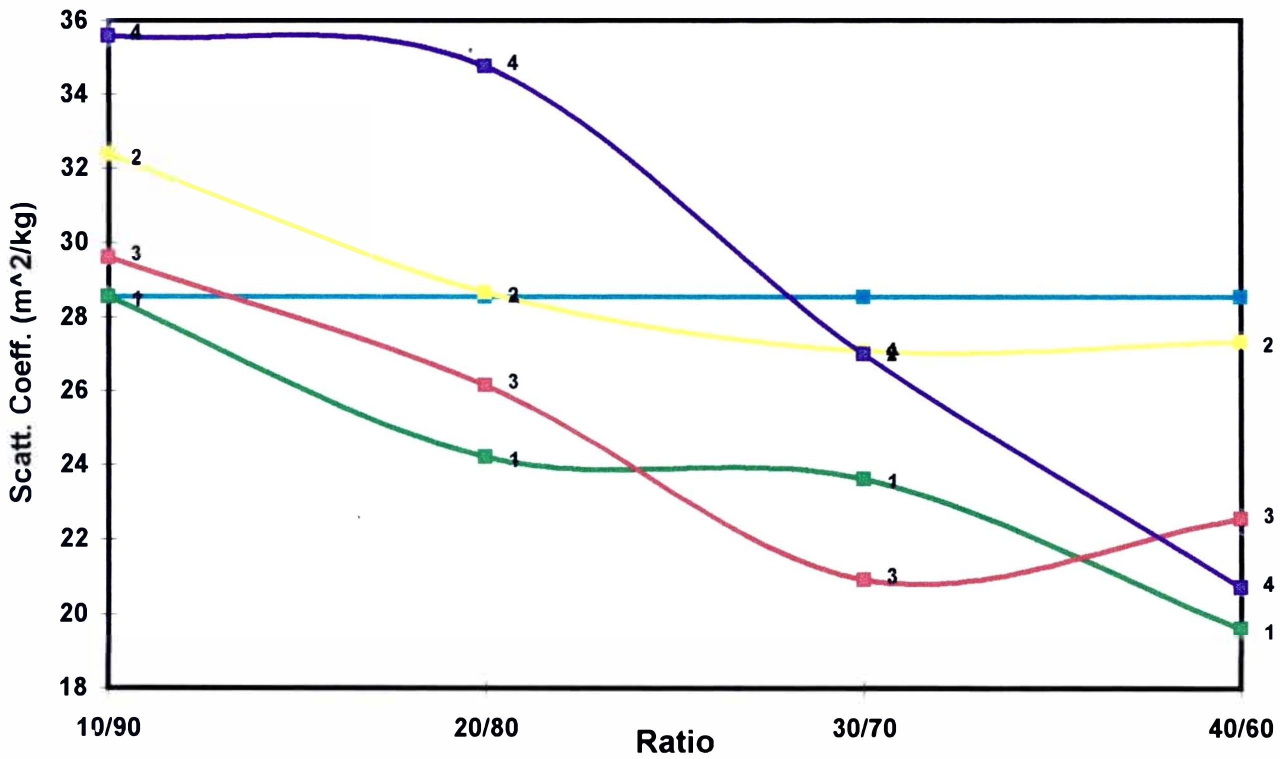


Figure 6-19: Fiber Ratio Effects



CHAPTER VII

DISCUSSION

Before a discussion can be presented on the handsheet properties it is necessary to discuss the general effects of recycling on fibers. This is needed to gain a better understanding of why the handsheets are being affected by recycling. It also gives a better understanding of how the screening worked.

Effect of Recycling on Short Fiber

The short fiber percentage was calculated as the moisture-free weight of short fiber passing through the 100 mesh screen divided by the total pulp weight. Table 7-1 shows the short fiber percentage over four recycles.

Table 7-1: Short Fiber Percentage

Recycle Number	Short Fiber Percentage,%
1	11.7
2	11.9
3	12.2
4	12.6

It can be seen that the percentage of short fiber increased for each successive recycle. The production of short fiber is the result of the cutting action that fibers receive during recycling. This is the accepted theory in recycling and accounts for a majority of the paper degradation during recycling. Figure 6-1 shows that approxiametly 85% of the short fiber present in a sample was fractionated from the long fiber during screening. The remaining 15% was retained within the long fiber due to flocculation or retention in the pulp mat that formed on the screens. This allows for accurate results to be achieved from the fractionated sheets.[1]

HANDSHEET STRENGTH PROPERTIES

Tensile Strength

Paper is a randomly bonded network of cellulose fibers whose tensile strength is controlled by both fiber strength and bond strength. Table 7-2 is a straightforward representation of the tensile strengths obtained during this experiment. Figures 6-2 and 6-3 represent the tensile indexes for the various fiber ratios and recycles.[4]

Table 7-2: Tensile Strength, Nm^2/g

Recycle	10/90	+/-	20/80	+/-	30/70	+/-	40/60	+/-
1	39.32	1.12	37.76	0.06	37.19	1.86	36.08	1.01
2	35.69	1.16	36.82	2.06	39.42	0.39	39.65	0.82
3	34.93	0.26	35.09	2.29	36.18	1.13	38.08	1.38
4	37.30	0.88	37.07	2.01	34.39	1.10	33.87	1.97

It can be seen in Figure 6-2 that the short fiber ratio has a direct effect on the tensile index during recycling. For the smaller short fiber ratios, the handsheets experienced a decreasing tensile strength over the first three recycles and then an increase at the fourth recycle. At the larger short fiber ratios, the tensile strength increased over the first two recycles and then proceeded to decrease over the next two. This is attributed to the split dependence of tensile strength on bond and fiber strength. At the lower ratios of fines the fiber strength is more prominent than the bond strength. The presence of shorter fibers creates an overall lower fiber strength. Also, the low short fiber ratio decreases the overall bond potential. As the fibers are recycled they become shorter and weaker, thus the decreasing trend. The increase at the fourth recycle occurs due to the long fiber receiving enough treatment to increase their overall bond ability. This treatment unravels the long fibers creating more bond area. The opposite can be said for the higher short fiber fractions. At the first two recycles the fibers have not experienced the degree of unraveling that the third and fourth recycle have, but the high short fiber fraction enables bond potential to be increased. A larger number of short fibers results in a decrease in the fiber strength portion of the tensile index along with an increase in the bond strength. As the fibers are continuously recycled the long and short fibers both under go the unraveling. This degrades the short fiber to a point were fiber strength is greatly reduced. Since short fiber is present in such high ratios the overall tensile strength decreases as it is recycled. The increase occurring over the first two recycles occurs due to fibers not being degraded as much as in the third and fourth recycles. The addition of short fiber increases bond potential, thus increasing tensile strength.[3]

The ability to duplicate a virgin thermomechanical paper using fractionation is best shown in Figure 6-3. The virgin thermomechanical paper is represented as the light blue line on the figure. To allow for a comparison to a virgin paper the control sheet was not fractionated, this was done to best imitate a mill environment. Using the figure along with the standard deviations in Table 7-2 a conclusion can be made as to what ratio of recycled fiber would best represent a virgin paper. It was determined that using a 20/80 short-to-long fiber ratio would give the closest comparison over a four recycle period, to a virgin paper. The third recycle represented on the figure had a high standard deviation which accounts for the low tensile strength value.

Tear Strength

Tear strength gives an indication of the force required to delaminate the handsheet and break the fiber. It is therefore a direct measurement of the fiber strength within the sheet. Table 7-3 shows the tear strength values and their standard deviations.[4]

Table 7-3: Tear Strength, mNm^2/g

Recycle #	10/90	+/-	20/80	+/-	30/70	+/-	40/60	+/-
1	9.21	0.26	8.49	0.69	7.94	0.69	7.76	0.66
2	9.06	0.49	8.43	0.44	7.65	0.39	7.36	0.60
3	7.07	0.28	8.51	0.69	7.70	0.62	6.65	0.47
4	6.23	1.76	6.02	0.33	5.73	0.12	5.92	0.33

The general effects of recycling on the tear strength can be seen on Figure 6-4. For each represented ratio the tear strength experienced a decreasing trend over the four recycle period. The decreasing of tear strength is attributed to the TMP fibers being "unraveled" during recycling. This unraveling effect decreases overall fiber strength. At the 20/80 and 30/70 ratio, for the first three recycles very little change was observed. This is attributed to the higher long fiber ratios present. The higher long fiber ratios are able to offset the effects of recycling. This trend should be represented in the 10/90 ratio. The third recycle does not follow the general trend for the 10/90 ratio. This is attributed to experimental error. The effects of recycling offset the higher long fiber ratios in the fourth recycle resulting in the large decrease in tear strength.[3]

The effects of fiber ratio on tear are demonstrated in Figure 6-5. Shown on the figure, as the short fiber fraction increases the tear strength decreases. This is representative of long fibers being generally stronger than short fibers. The presence of long fibers also creates a greater probability that a fiber will be in the area that the tear tester is applying its force. The more fiber in the given area the greater the tear strength will be.[3]

Matching the tear strength of a virgin paper with recycled fiber is very difficult. This is due to the continued shortening of the fibers, which in return reduces the tear strength. As seen on Figure 6-5, the use of a 30/70 ratio allows for tear strength to be duplicated up to the fourth recycle. At the fourth recycle, each of the four ratios experienced a severe decrease in the tear strength. This suggests that the only way to offset the effects of recycling after the third recycle would be to add virgin fiber to the recycle slurry.

Burst Strength

Burst strength is a measure of the puncture resistance of a sheet of paper. It is therefore directly related to the bonding strength of the sheet. Table 7-4 represents the burst indexes and their standard deviations for this experiment.[4]

The effects of recycling on the burst strength are shown on Figure 6-6. For each ratio the burst strength is shown to decrease for the first three recycles and then increase at the fourth recycle. The exception occurs in the 40/60 ratio were the burst strength continues to decrease through the fourth recycle. The decrease in burst strength at the lower ratios can be attributed to the lower overall bond area of the short fiber ratio paper. The burst strength for the first two recycles remains relatively constant for the three largest short fiber ratios. This is attributed to the recycling effects not being as pronounced at this point and the short fibers present are able to form strong bonds in the void areas between long fibers. After the second recycle the unraveling of the fibers begins decreasing the bonding ability of the sheet. The unraveled fibers have less overall bond area than those of previous recycles. The increase of the fourth recycle may be attributed to the shortening of the fibers during recycling which results in a larger number of fibers being introduced in a given area. The large number of fibers allows a greater number of bonds to be formed.[3]

Table 7-4: Burst Strength, $kPam^2/g$

Recycle #	10/90	+/-	20/80	+/-	30/70	+/-	40/60	+/-
1	2.12	0.17	2.19	0.22	2.22	0.15	2.25	0.29
2	1.79	0.48	2.21	0.06	2.19	0.16	2.25	0.14
3	1.57	0.15	1.63	0.15	1.70	0.19	1.94	0.26
4	2.06	0.02	2.03	0.10	1.99	0.08	1.72	0.06

The effects of fiber fraction on the burst strength is represented on Figure 6-7. The figure shows that burst strength increases with higher short fiber ratios for the first three recycles. The fourth recycle is shown to decrease as short fiber ratio is increased. The increase over the first three recycles is attributed to the increase in short fiber ratio. The higher short fiber ratios allow for a greater bond potential to be achieved. This is due to the short fiber filling voids in the sheet and creating bonds. The decrease experienced in the fourth recycle is mainly the result of the recycling effects on the fiber being more pronounced. The more the fibers were recycled the greater the unraveling effect. As the fibers were unraveled to a greater extent the loss of bond area became more prominent than the addition of short fiber could compensate for.[3]

The ability to match the burst strength of a virgin TMP paper is demonstrated on Figures 6-6 and 6-7. As the figures show there is no set ratio, over four recycles, resulting in burst strengths similar to that of the control. Taking the standard deviations into account, the best overall results are achieved at the 30/70 ratio.

Zero-Span Strength

The zero-span strength of a sheet of paper is directly related to the fiber strength and in theory the bond strength. Table 7-5 represents the zero-span strength for this experiment.[4]

Table 7-5: Zero-Span Strength, psi

Recycle #	10/90	+/-	20/80	+/-	30/70	+/-	40/60	+/-
1	44.20	7.44	54.40	6.72	61.40	7.92	72.20	3.44
2	37.40	4.72	37.00	5.20	52.60	4.72	62.00	2.00
3	35.60	3.28	30.00	2.00	35.60	2.88	39.00	0.80
4	55.20	3.36	57.20	3.36	56.20	1.92	61.40	2.08

The sheets for each ratio experienced the same general effects from recycling. For the first three recycles the zero-span strength decreased and then increased at the fourth recycle. This is attributed to the fiber strength being degraded during recycling. The large increase at the fourth recycle is somewhat unexpected because the recycling should have continued to degrade the fiber strength. This may be the result of a greater number of short fibers being produced over the recycles. These shorter fibers are able to align in the z-direction in the sheet. This in return gives the sheet a greater z-direction strength.

Each recycle shows the same effects of increasing zero-span strength with increased short fiber ratio. This supports the above assumption that short fibers are able to align in the z-direction giving the paper greater strength in this direction. It also supports the idea that zero-span is also dependent on bond strength. The shorter fibers result in a greater bond area per unit area in the sheet.

The high standard deviations presented in Table 7-5 make the comparison to the virgin paper difficult. Taking the standard deviations into account it can be seen that a 30/70 ratio will result in a recycled paper with similar characteristics to that of the virgin sheet. This is despite the third recycle it considerably lower than the control sheet in terms of zero-span strength.

PHYSICAL PROPERTIES

Density

Density is a direct measure of the mass per unit area in a given handsheet. Table 7-6 represents the various density measurements obtained for this experiment. These results are expressed graphically on Figures 6-10 and 6-11.[4]

The density is directly affected by recycling and short fiber fraction. Short fibers are able to compact more readily in a given volume, this gives the sheet a greater mass per unit volume. The recycling of a mechanical fiber creates a more flexible and flatter fiber. The flexibility and flatness give the fibers the ability to form a compact sheet. The addition of short fibers allows the filling of void areas creating greater mass in the given

Table 7-6: Density, g/cm^3

Recycle #	10/90	20/80	30/70	40/60
1	0.38	0.38	0.40	0.40
2	0.38	0.39	0.42	0.44
3	0.40	0.39	0.38	0.44
4	0.44	0.45	0.48	0.46

volume. Figures 6-10 and 6-11 reflect these trends with a few exceptions. At the 30/70 ratio in the third recycle the density experienced a slight decrease. This is reflective of the lower average basis weight of these sheets, see Table 6-3. Figure 6-11 shows that the third recycle density decreases with an increased short fiber ratio. This is also attributed to the lower average basis weights shown in Tables 6-1 through 6-4. The comparison of density values to that of the control cannot be established in an accurate means. This is due to the variations in basis weights that are demonstrated throughout the four recycles. Slight variations in basis weight reflect directly on the density of the individual sheets.[1]

Air Resistance

The air resistance is a direct measure of the time that is required to pass a given volume of air through a sheet. Table 7-6 is representative of the porosity values in this experiment, in terms of seconds per 100 milliliters.[4]

Air Resistance is directly related to the density of a sheet. For this reason, air resistance shows the same general trends as density when compared against recycling and short fiber ratio. The denser the sheet the more time is going to be required to pass a given volume of air through it. This is due to the denser sheet containing smaller void area which the air readily passes through. By recycling or increasing short fiber ratio the void area is reduced. As seen in Figures 6-12 and 6-13 the greatest air resistance values are seen at the higher ratios along with the third and fourth recycles. Figure 6-12 also shows that the air resistance of the control sheet can be matched by addition of 20% short fiber. The air resistance can be matched over all four recycles within a few seconds.[1]

Table 7-7: Porosity, sec/100ml

Recycle #	10/90	20/80	30/70	40/60
1	13.50	31.50	44.88	67.10
2	17.60	30.90	52.25	72.75
3	19.95	38.70	105.25	119.20
4	38.00	46.65	107.23	126.25

OPTICAL PROPERTIES

Opacity

Opacity is calculated as the contrast ratio between the reflectance value of a single sheet backed by a non-reflecting black surface and that of a pile of sheets of the same material. Table 7-8 represents the opacity values collected during this experiment.[4]

Figures 6-14 and 6-15 show the opacity in terms of recycling and short fiber ratio addition. As seen on the figures, no definite trend is observed through four recycles and short fiber addition. Overall, the opacity decreases with short fiber addition. The increase in short fiber reflects a decrease in the number of air voids. The decrease in air voids leads to fewer angles to reflect the light off. The addition of short fiber creates a "flatter" surface for the light to encounter, thus light is not reflected.[1]

Table 7-8: Opacity, %

Recycle #	10/90	20/80	30/70	40/60
1	99.65	98.70	98.64	97.95
2	99.65	98.59	99.65	99.41
3	99.67	99.36	98.15	99.38
4	99.88	99.89	99.50	98.64

The effects of recycling cannot be readily determined from the data collected. Figure 6-14 shows that no trend was developed over the recycling carried out in this experiment. For this reason no reasonable comparison to the control sheet can be made. According to previous research done with mechanical pulp, opacity should decrease over recycles in theory. This again is do to the reduction in air void space within the sheet.

Brightness

Brightness is measured as the amount of reflectance a given sheet has when compared to magnesium oxide, which is considered 100% bright. Table 7-9 represents the brightness values obtained in this experiment.[4]

The overall effects of recycling are shown on Figure 6-16. The figure shows that brightness decreases with increased recycling. This is attributed to the higher reflectance of the recycled sheet. This trend is also observed with increased short fiber fraction. The lower the reflectance the lower the brightness of the sheet.[1]

Table 7-9: Brightness, %

Recycle #	10/90	20/80	30/70	40/60
1	38.63	38.00	36.67	36.07
2	36.67	35.98	35.14	33.92
3	33.85	33.50	33.00	30.60
4	33.02	32.38	30.93	30.81

The ability to match a virgin sheet using fiber ratio control was not feasible in this study. The addition of short fiber directly negates the ability to match the brightness of a sheet. In order to match brightness values of a virgin sheet would require the addition of some type of brightening agent, like a filler.

Scattering Coefficient

The scattering coefficient measures the sheets ability to scatter light. Table 7-10 represents the scattering coefficients for this experiment.[4]

The data presented in Figure 6-19 represents the effects of short fiber on the scattering coefficient. By increasing the short fiber ratio, the scattering coefficient will

Table 7-10: Scattering Coefficient, m^2/kg

Recycle #	10/90	20/80	30/70	40/60
1	32.69	24.21	23.62	19.62
2	32.38	28.67	27.10	27.34
3	29.60	26.16	20.94	22.56
4	35.58	34.75	27.01	20.72

decrease. This is mainly due to a denser sheet being unable to scatter light as readily. The density of the sheet prevents light from being readily scattered once it is emitted on the sheet. When light enters a less dense sheet it is able to reflect off in several different directions, thus the higher scattering coefficient.[1]

The general effects of recycling are shown in Figure 6-18. The figure shows that second and fourth recycle values are higher than those achieved during the first and third recycles. The scattering coefficient should increase over recycles due to the unraveling of the fibers. This unraveling distributes the fibers in the sheet which in return reflects the light more readily. The reflecting of the light results in the increased scattering coefficients.

CHAPTER VIII

CONCLUSION

The general effects of recycling and fiber ratios on the thermomechanical sheets properties have been evaluated. Also, the practicality of using fractionation as a means of duplicating virgin TMP paper properties has been experimentally examined. From the data collected several conclusions can be made:

1. Tensile strength is dependent on both the fiber and bond strength. Recycling degrades fiber strength, but leads to fiber flexibility. The flexibility allows for higher bonding potential between fibers. The addition of short fibers increases bond potential with a decrease in overall fiber strength.
2. Tear strength is decreased through recycling and short fiber addition. This is directly caused by the recycled fiber and short fibers having lower overall fiber strength.
3. Burst strength increases with an increased bond potential. For this reason, short fiber addition will increase the burst strength. Recycling leads to an increase in burst strength until the effects of recycling offset the increase. Continuous recycling unravels the fibers decreasing their bond area resulting in the decrease in burst strength.

4. Zero-span strength is directly related to the fiber strength. The continued recycling of sheets degrades fibers resulting in lower zero-span strength. This continues until the fourth recycle were the fibers are short enough to align themselves in the z-direction resulting in a stronger sheet in this direction. The addition of short fibers also leads to an increase in zero-span strength supporting the previous statement.
5. Air Resistance and density are directly related. The denser the sheet the more time is required to pass a given volume of air through the sheet. Recycling and adding short fiber lead to a denser sheet thus a greater air resistance.
6. Continued recycling of a sheet reduces the brightness as does short fiber addition.
7. Scattering Coefficient was shown to be dependent on the fines content. It was shown as fines content increase the scattering coefficient decreases.
8. The ability to match a virgin sheet using fractionation was shown to be possible in terms of strength, see table 8-1.

Table 8-1: Duplication of Virgin TMP Paper Properties

Property	10/90	20/80	30/70	40/60
Tensile	no	**yes**	no	no
Tear	no	no	**yes**	no
Burst	no	no	**yes**	no
Zero-Span	no	no	**yes**	no
Porosity	no	**yes**	no	no
Opacity	no	no	no	no
Brightness	no	no	no	no
Scatt. Coeff.	no	no	no	no

CHAPTER IX

SUGGESTIONS FOR FURTHER RESEARCH

It is recommended to narrow the ratios used. Ratios between 16/84 to 36/64 at every 4% would narrow the research down. This would also give a better understanding of exactly what point properties are matched between virgin and recycled fiber.

Obtaining a sample of pulp and finished product from a writing grade paper. Perform the experiment in the same manner with the narrow ratio range. This would be more applicable to industry since recycling is having the greatest negative effect on this type of paper. The sample fo final product would give a better control sample to compare results to. This could also be done on a sample of mixed office waste. This would also imitate real mill conditions and give a more reasonable idea of the applicability of fractionation.

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