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The Effects of Repeated Recycle on Paper Strength

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THE EFFECTS OF REPEATED RECYCLE ON PAPER STRENGTH

BY

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abstract

As society stresses the need to recycle to reduce the amount of waste sent to our municipality landfills every year, the effect of secondary fiber on the papers that we produce becomes greater and greater. One of the largest effects that these fibers have is to change the strength properties in the sheets which contain them. Most studies have shown a decrease in the tensile strength of paper as fibers pass repeatedly through a series of recycle. The reason for this tendency is believed to be a loss of bonding potential between fibers as they become shorter and stiffer through a process known as irreversible hornification.

Four grades were chosen to observe the effects upon sheet strength when passed through a series of five recycles. The grades covered a range of softwood to hardwood ratios, of filler content, and of degree of refining in the initial sheet. In all cases, tensile strength was shown to increase over the first three to four recycles before beginning to decrease with further recycle. Tests indicate that the leaching of filler from these relatively highly filled sheets was the main reson for these unusual, but not unprecedented results. As the filler is removed from the sheet, more bonding sites between fibers become available. This allows for higher strength within the sheet until this effect becomes increasingly offset by the hornification of the fibers, at which point strength begins to deteriorate.

The hypothesis of filler loss is strengthened by general decreases in brightness and opacity through successive stages of recycle. As these fillers are used expressly to enhance these sheet properties in these grades, it is apparent that they are being removed during the sheet formation process. Tear strength was shown to decrease through the course of this investigation, a result which is consistent with a rise in tensile strength.

Fiber length analysis and ash testing of sample sheets would further aid in evaluation as to the extent to which fiber shortening and the loss of filler affect the strength properties of sheets made from repeeatedly recycled fibers.

William T. Byrd

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introduction

The societal demand for increased recycling has added many new variables to the science of papermaking. The effect of increasing the percentage of secondary fibers on the strength of the resulting sheet is one of these variables. In an effort to keep up with secondary fiber requirements, many mills have been forced to look elsewhere for sources of broke compatible with their own processes. This practice leads many times to the introduction of an unknown element into the papermaking process.

Although studies have been done to assess the effects of repeated recycle on particular fiber types, and even more specifically on individual tree species, this is seldom the situation which is dealt with when stock is recycled in the mill setting. When broke is added to the furnish of a paper machine, the dynamics which will ultimately decide the properties of the finished sheet are much more complex than this. This study will analyze the effects of repeated recycle on the strength properties of four distinct grades of paper as they are repulped and sheets are reformed through five consecutive stages of recycle. These grades cover a range of softwood to hardwood ratios, of filler content, and of degree of refining in the base stocks of these grades.

The results of this study will hopefully shed some insight as to how these factors influence the properties of the final sheet and may be a valuable resource when attempting to predict the strength compatibility of sources of broke based upon the components and treatment of the initial stock.

theoretical and background discussion

Studies regarding the effect of repeated recycle on the strength properties of paper have shown quite varied results. This is not surprising when one examines the variety of test methods and furishes which have been studied. Experiments have been conducted utilizing British Standard handsheet molds, Noble & Wood handsheet formers, pilot paper machines, and combinations of these methods. Furnishes studied have included bleached and unbleached chemical pulps, mechanical pulps, and blends of pulps with different initial treatments. Studies have focused on pulps which have been beaten at each stage to a specific freeness value while some machine trials have aimed at reaching a specific value for a certain paper property, such as density or breaking length, with each recycle. Despite the wide range of variation amongst tests, most studies have shown some degree of strength loss in paper with repeated recycle. Horn (5) reported a 33% decrease in fiber strength for an unbleached southern pine pulp, and Ellis and Sedlacek (4) showed zero-span breaking length ratios (6th recycle to 1st recycle) of 0.91 for southern bleached pine Kraft pulp, 0.93 for southern unbleached pine Kraft pulp, and 0.86 for unbleached Kraft hardwood pulp. There have been instances of tests which have shown strength increases in sheets following successive recycles. Bobalek (1) reported increases of 7% for southern pine and 19% for eucalyptus fibers.

Factors which have been most commonly stated as important to the strength of sheets produced from recycled fibers include fiber strength, fiber length, fiber swelling/plasticity, and fiber bonding potential (1,5,7,8). Although some investigations have shown decreases (3,5) and others have shown increases in fiber strength (1), this has been shown to be more a function of the fiber species and degree of chemical treament than of degree of recycle. The explanation given for the decrease in paper strength properties has most often been a loss of the ability of the fibers in the sheet to bond well with each other. This phenomenon has been called irreversible hornification, which is in actuality a stiffening or hardening of the fiber. It has been suggested that this stiffening or hardening after each drying produces a fiber which, while still maintaining its independent strength, does not have the flexibility nor the amount of bonding sites along its length to conform well to other fibers and then to bond well once it has achieved this position. Using water retention value (WRV) to measure the swelling capacity of fibers, McKee (8) found swelling to decrease with subsequent recycle, with the most noticeable losses occurring during the first two recycles. Yamagishi and Oye (4) showed similar results with hardwood and softwood bleached Kraft pulps, with WRV decreasing 13% between the first two recycles in each case. Lundberg and de Ruvo found there to be a direct relationship between WRV and tensile strength in their tests with bleached birch and SGW pulps (4), and Fellars (4) noted that recycled fibers beaten to the same degree of swelling as virgin fibers produced paper with equivalent strength properties. Bovin's (2) work with recycled fiber sheets prepared at constant density confirmed these results.

Van Wyk and Gerischer (4) studied the influence of repeated recycle on paper made on a laboratory fourdrinier using a bleached sulfite pulp refined to a freeness of 38 SR. Their findings showed a decrease in nearly all paper strength properties up to the fourth recycle, after which the rate of strength decrease slowed considerably. Their data showed little change in the zero-span tensile strength of the fibers, and their conclusion was that the strength decrease was related much more closely to a loss of interfiber bonding. Bobalek and Chaturvedi (1) showed that zero-span tensile remained constant over the course of three successive recycles as well.

Yamagishi and Oye examined the effects of repeated recycle on hardwood and softwood bleached Kraft pulps beaten to a single freeness level (4).

Consistent with the work of Van Wyk and Gerischer, their data showed decreases in breaking length and density. Tear factor was shown to increase for the hardwood pulp but to decrease for the softwood pulp.

Lundberg and de Ruvo (4) found that the single factor which was most closely associated with fiber swelling was drying of the sheet. Their results showed that higher drying temperatures produced less swelling and restrained drying reduced the swelling even more. These tests were done on a commercial, never dried bleached Kraft pulp which they then dried at 20 and 120 degrees Celsius. Jayme (6) showed similar results with a.d. pulp and pulp dried at 70 degrees Celsius. Lundberg (4) reported that pulp which had been dried at higher temperatures was unable to regain the WRV of the initial pulp even with extensive beating.

procedure

1. Procure samples of four different grades of paper to be recycled.

2. Take 30 g of each sample and dilute with 500 g of water to obtain a slurry of approximately 5.5%. This should allow for approximately 20 handsheets to be produced for each grade. For each level of recycle, the best 10 sheets will be used for testing. All sheets, including the scraps from the testing process, will be used for the next recycle. This should offset any losses which will occur during the process and guarantee 10 good sheets for the fifth recycle.

3. Soak samples in water at room temperature for 1 hour.

4. Repulp stock samples in Waring blender at high speed for 15 minutes.

5. Form handsheets in modified Noble & Wood handsheet maker with a target of 1.5 g per handsheet.

6. Dry sheets on hotplate at 425 degrees for 5 minutes.

7. Take ten best sheets and use for testing after conditioning for 24 hours. Tests will consist of tensile, tear, brightness, and opacity.

8. Collect all of the handsheets and trim from testing to be used as stock for the next level of recycle.

9. Repeat process from step #2 adjusting water addition for fiber losses so that consistency remains as close to 5.5% as is possible for each successive recycle.

table 1: averaged test values for all test grades

RECYCLE #	GRADE #1 TENSILE	TEAR	BRIGHTNESS	OPACITY
1	5.096	37.06	80.22	85.44
2	6.418	37.72	77.17	86.29
3	6.496	33.25	74.29	85.21
4	6.863	34.80	71.32	81.99
5	6.470	39.06	68.25	80.74
RATIO 5:1	**1.27**	**1.05**	**0.85**	**0.94**

RECYCLE #	GRADE #2 TENSILE	TEAR	BRIGHTNESS	OPACITY
1	7.839	50.13	22.77	62.91
2	8.582	48.78	23.22	63.49
3	9.292	45.38	22.04	60.97
4	8.628	46.75	22.84	59.36
5	8.628	46.06	22.84	57.68
RATIO 5:1	**1.1**	**0.91**	**1**	**0.91**

RECYCLE #	GRADE #3 TENSILE	TEAR	BRIGHTNESS	OPACITY
1	5.031	35.19	73.6	79.49
2	5.697	35.72	71.44	80.97
3	6.420	35.88	68.84	78.16
4	5.637	34.38	67.04	76.91
5	5.631	29.38	65.13	77.12
RATIO 5:1	**1.12**	**0.83**	**0.88**	**0.97**

RECYCLE #	GRADE #4 TENSILE	TEAR	BRIGHTNESS	OPACITY
1	2.853	37.00	76.47	78.59
2	6.559	38.28	72.42	82.28
3	6.418	36.06	70.51	77.54
4	5.345	34.69	68.77	76.46
5	5.422	34.81	66.05	75.61
RATIO 5:1	**1.9**	**0.94**	**0.86**	**0.96**

figure 1: the effect of recycle level on tensile strength

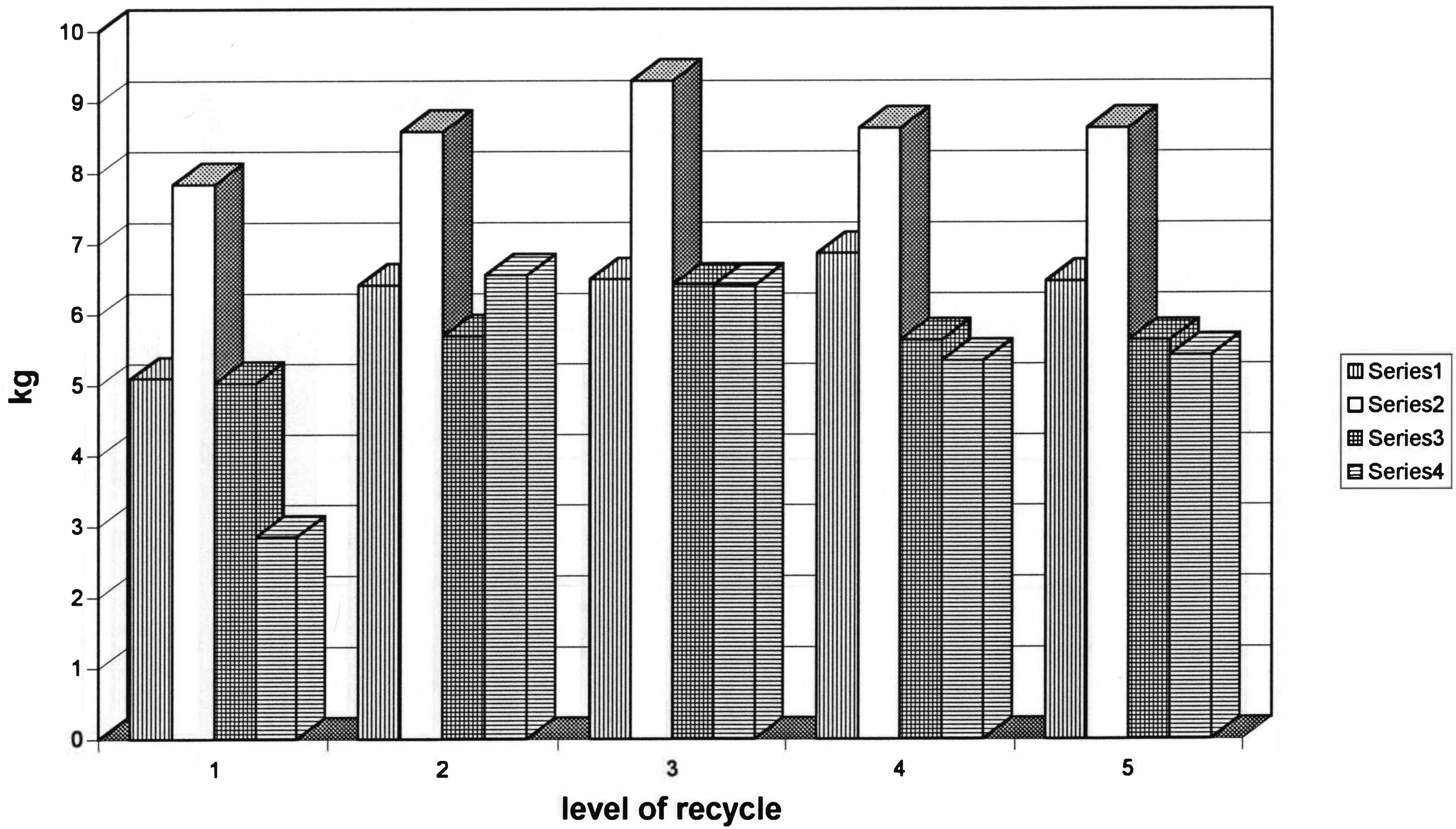


figure 2: the effect of recycle level on tear strength

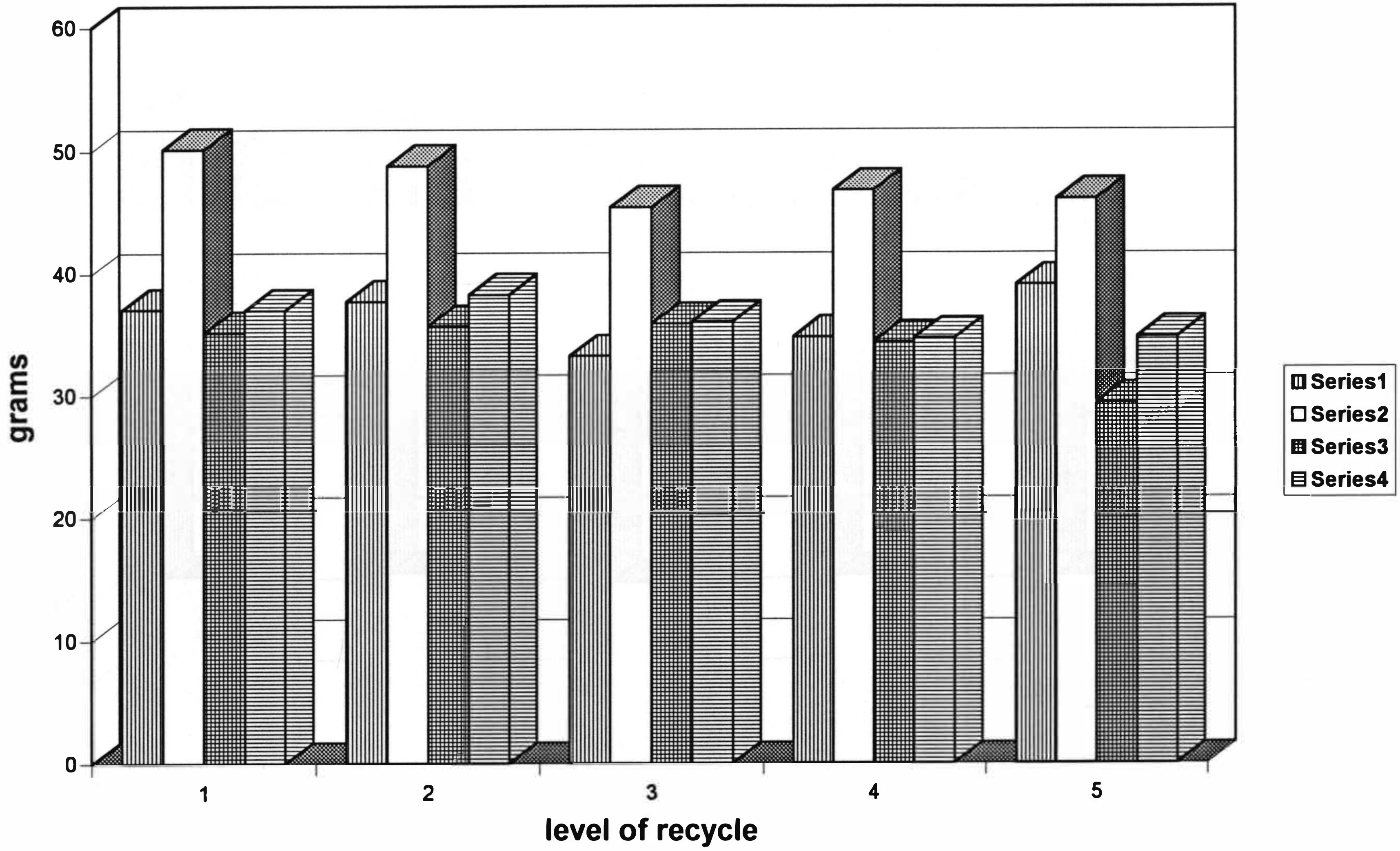


figure 3: the effect of recycle level on brightness

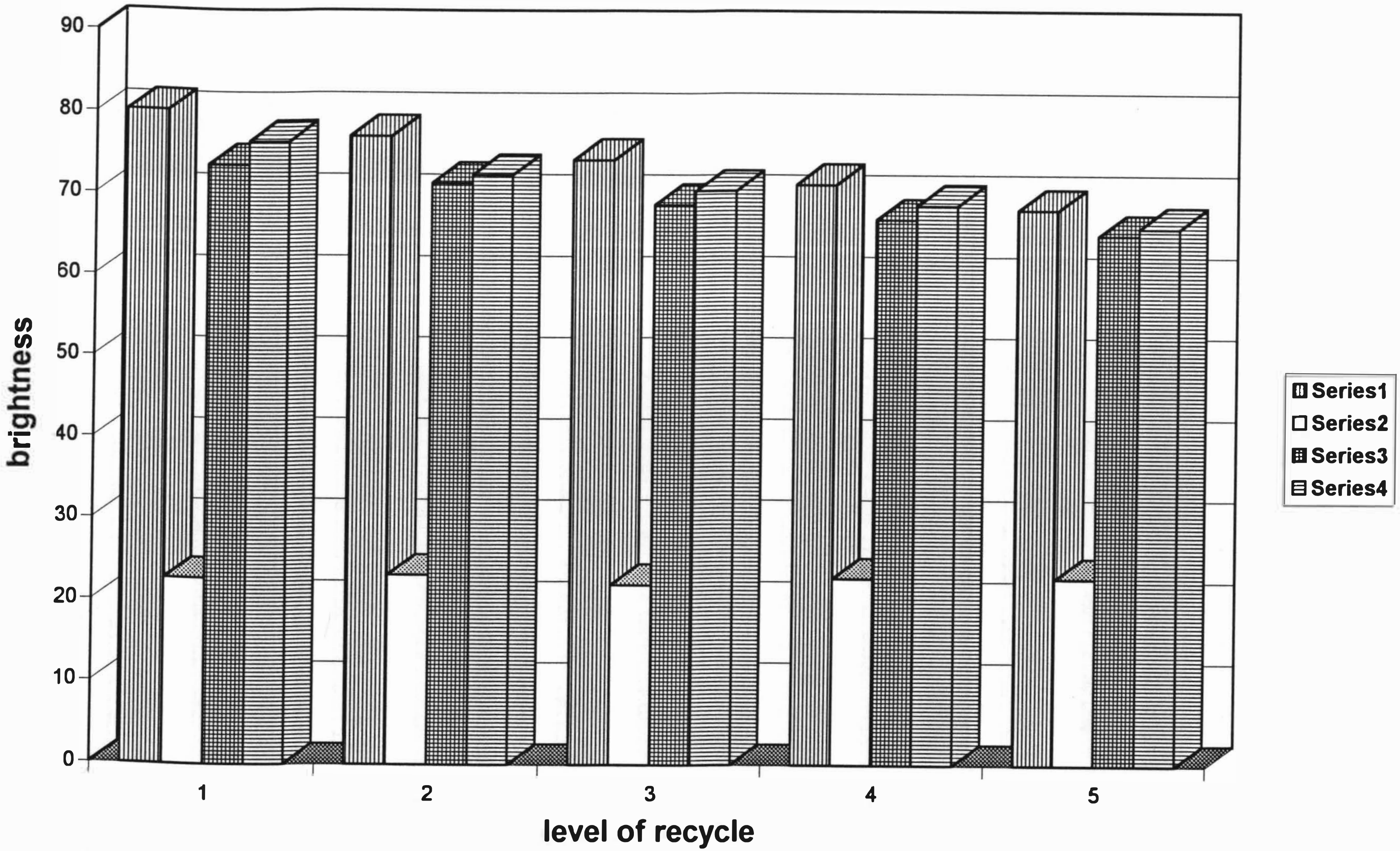
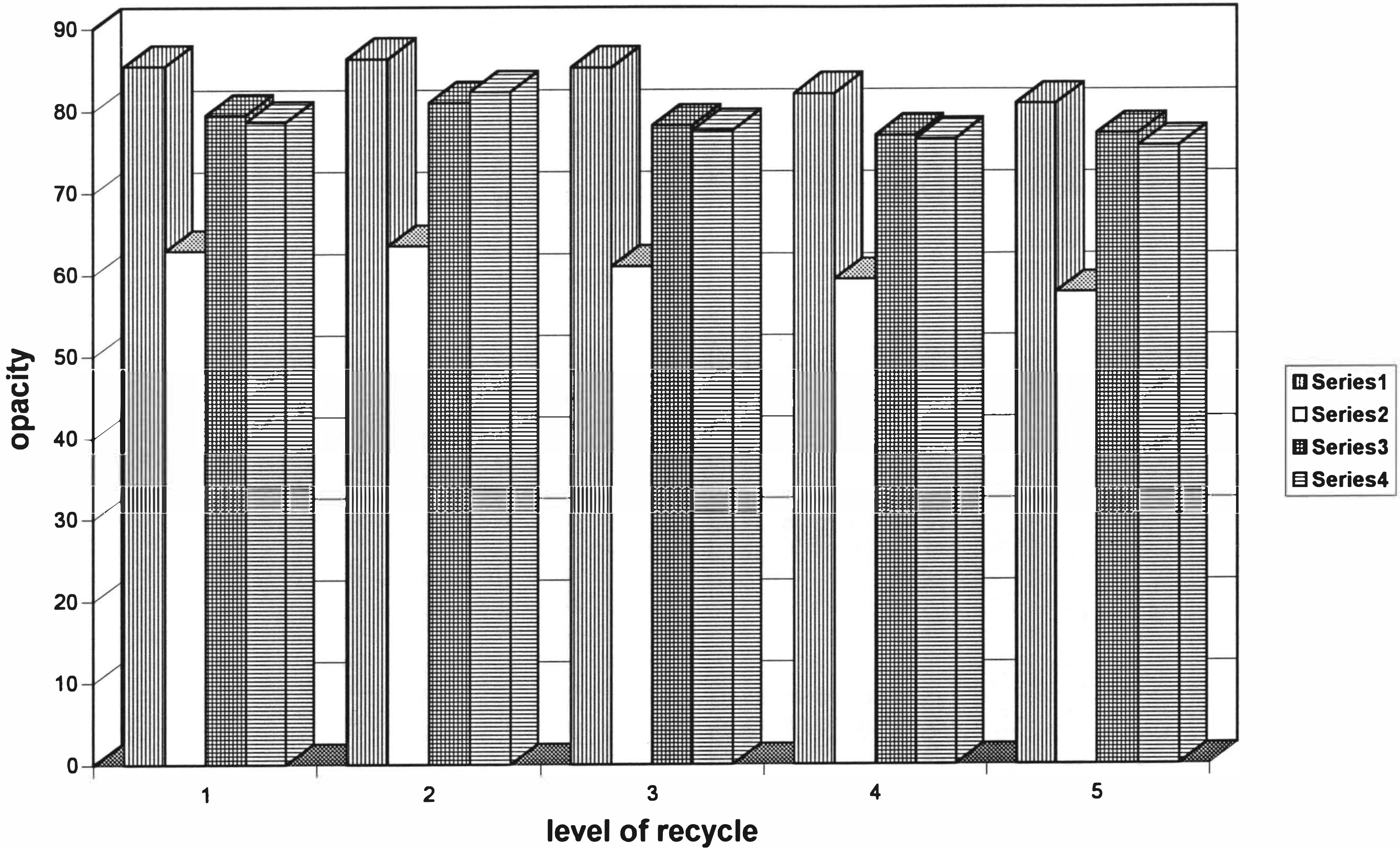


figure 4: the effect of recycle level on opacity



discussion of results

The four pulps which have been studied contain different blends of softwood to hardwood, have undergone different levels of initial refining, and contain different levels of filler in their stock furnishes. (See appendix I)

RECYCLE #	**GRADE #1 TENSILE**	**GRADE #2 TENSILE**	**GRADE #3 TENSILE**	**GRADE #4 TENSILE**
1	5.096	7.839	5.031	2.853
2	6.418	8.582	5.697	6.559
3	6.496	9.292	6.420	6.418
4	6.863	8.628	5.637	5.345
5	6.470	8.628	5.631	5.422
RATIO 5:1	**1.27**	**1.1**	**1.12**	**1.9**

As can be seen from the data, every grade of paper showed an increase in the tensile strength of sheets over the series of five recycles. These results, although inconsistent with the majority of data found in the literature, may still be able to be explained by the theories presented in the background discussion. Although these pulps may be regaining some degree of their initial water retention value due to the 15 minutes of repulping in the Waring blender prior to sheet formation, the reason for the increase in paper strength in these samples more likely is attributable to a decrease in the amount of filler present in the sheet from recycle to recycle. These grades are all highly refined and there is little chance that what is being seen is increased fibrillation due to the action of the blender on the pulp. Instead, these highly filled sheets may be seeing a leaching away of the fillers used to produce high brightness and opacity in the sheets. This high filler content may be helping to cause the tensile strength to increase over the series of recycles in two ways. Firstly, the filler in the initial sheet prevents all of the possible bonding sites to be used by adjacent fibers. This would lead to secondary stock which has not really achieved all of the potential strength which the high levels of refining would usually provide. Secondly, as this filler leaches out of the sheet during handsheet formation, the overall percentage of filler in successive recycles would decrease. This would allow for more bonding sites between fibers at each successive stage and may account for the initial increases in tensile strength for these grades.

Grades 1 and 2 have the highest level of filler of the four samples. Grade #1 shows tensile strength increases for the first four stages of recycle, while grade #2 shows increases through 3 stages of recycling. Grade #3, with slightly less filler, shows increases through the first 3 recycles as well. The data for grade #4 is unreliable because of an error during the experimental portion of this investigation. While redispersing in the Waring blender, a seal in the bottom of the blender leaked and quite a bit of water was lost. As a result, this grade was repulped initially at a much higher consistency than were the rest of the samples. The result was that the stock was not as well dispersed and appendix VI shows the result. This marbleized sheet provided much lower strength values for the first recycle than the other three samples and this resulted in a much larger ratio for the first to fifth recycle than would otherwise have occurred. The data have been included for completeness, but this error should be noted when attempting to draw any correlations between this grade and the other three in this study.

For all four grades, a point was reached at the 3rd or 4th recycle when the dynamics of the system became such that the tensile increases experienced up to that point were no longer seen. Most likely the additional bonding sites which resulted from the repeated loss of filler were maximized and the hornification of the fiber at this point began to become the most prominent factor in the strength of the resulting sheets.

RECYCLE #	GRADE #1 BRIGHTNESS	GRADE #2 BRIGHTNESS	GRADE #3 BRIGHTNESS	GRADE #4 BRIGHTNESS
1	80.22	22.77	73.6	76.47
2	77.17	23.22	71.44	72.42
3	74.29	22.04	68.84	70.51
4	71.32	22.84	67.04	68.77
5	68.25	22.84	65.13	66.05
RATIO 5:1	**0.85**	**1**	**0.88**	**0.86**

The results of the brightness testing following each stage of recycle are in agreement with the hypothesis that the brightness enhancing filler are indeed being lost with each recycle. Grades 1,3, and 4 all show similar trends for brightness. In these grades, brightness decreased an average of 2 to 3 points with each recycle and the fifth to first recycle ratios are comparable as well. Grade #2 is the only colored grade amongst the test grades, and is the only one which contains unbleached fibers in its initial furnish. The initial increase in brightness (the only brightness increase encountered amongst all four grades) may be attributed to the loss of some of these unbleached fibers as fines, but the low brightness level of this grade makes comparison to the others difficult.

RECYCLE #	GRADE #1 OPACITY	GRADE #2 OPACITY	GRADE #3 OPACITY	GRADE #4 OPACITY
1	85.44	62.91	79.49	78.59
2	86.29	63.49	80.97	82.28
3	85.21	60.97	78.16	77.54
4	81.99	59.36	76.91	76.46
5	80.74	57.68	77.12	75.61
RATIO 5:1	**0.94**	**0.91**	**0.97**	**0.96**

The results of the opacity testing further support the idea that filler content in the sheet is decreasing with each recycle. All grades show an overall loss of opacity for the series of recycles. This would not ordinarily be expected to be witnessed with sheets which are showing decreases in tensile strength, but there are instances in this investigation which show decreased tensile strength (grade #1 - recycle #3 to recycle #4 for example) as well as decreased opacity. The decrease in tensile strength would normally be accompanied by an increase in opacity due to the loss of bonding and increased voids in the sheet. However, in these instances, it may be that the hornification of the fibers is the result of the strength decrease while the removal of fillers is the cause for the decrease in opacity. The results for grade #2 are included for completeness although this is a colored grade and opacity results have little correlation to the other test grades.

	GRADE #1	**GRADE #2**	**GRADE #3**	**GRADE #4**
RECYCLE #	**TEAR**	**TEAR**	**TEAR**	**TEAR**
1	37.06	50.13	35.19	37.00
2	37.72	48.78	35.72	38.28
3	33.25	45.38	35.88	36.06
4	34.80	46.75	34.38	34.69
5	39.06	46.06	29.38	34.81
RATIO 5:1	**1.05**	**0.91**	**0.83**	**0.94**

The results of the tear testing are in accord with the tensile results. Tear index is negatively affected by increased bonding in the sheet and shows an inverse relationship with bonding and tensile strength. All grades show decreases in tear strength over the series of recycles, with the exception of grade #1. Grade #1 shows an overall increase in tear strength over the course of the experiment, but the data is skewed by an unexplainable large increase in the tear values witnessed by the sheets produced following the fifth stage of recycle.

It would be insightful in this investigation to perform a fiber length analysis following each stage of recycle to witness the effects on the fibers of the Waring blender. There is probably some degree of fiber shortening taking place at each stage, but without this analysis it is impossible to quantify the effect that this physical operation has on the results of these tests. It would also be beneficial to perform an ash test on sheet samples following each stage of recycle to determine the extent to which the percentage of filler in the sheet is diminishing with each recycle. Again, the tests indicate that this is a major contributor to the results of this investigation, but quantification is difficult.

conclusions

1. All grades show initial increases in tensile strength for at least the first two levels of recycle. It is uncertain how much of this is a result of energy being put into the fibers during repulping and how much is a result of fillers and fines being removed from the sheet during recycle.

2. Highest gains in tensile strength associated with highest initial filler content.

3. Highest gains in tensile strength associated with highest softwood content.

4. All grades show an overall decrease in brightness and opacity. This is an indication that filler is being leached out in successive recycles and this may be allowing for more bonding sites between the remaining fibers.

5. The data shows no significant trends with respect to initial refining energy and resulting strength of sheets following recycle.

6. The only grade to show an increase in brightness was grade #2. This is a colored grade and is also the only grade to contain unbleached hardwood fibers. Removal of these fibers as fines during handsheet formation would leave a furnish which consists increasingly of bleached fibers. This is further evidence that fines and filler are being washed out of the sheet with each recycle.

recommendations

1. Fiber length analysis would be helpful at each level of recycle to determine the amount of fiber cutting which is taking place during the repulping phase of the experiment.

2. Ash test would be helpful to determine the degree to which fillers are being leached from the sheet during the handsheet formation portion of this study.

3. It would be helpful to repeat the experiment while collecting the water which drains out of the handsheet former. This could then be used in the next recycle as make-up water for the handsheets and comparison to the data presented in the current study would give an indication of the effects of fines buildup and filler retention in the recycling process.

literature cited

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appendix I - grade characteristics

1 = highest
2 = lowest

grade #1 - white tipping
- % softwood - 1
- deg. of refining - 1
- filler content - 1

grade #2 - cork tipping
- % softwood - 2
- deg. of refining - 2
- filler content - 1

grade #3 - business form
- % softwood - 4
- deg. of refining - 4
- filler content - 2

grade #4 - photo imaging
- % softwood - 3
- deg. of refining - 3
- filler content - 2

appendix II - raw data

Grade #1 - White Tipping

ranking amongst test grades (1=highest, 4=lowest)
% softwood - 1
degree of refining - 1
filler content - 1

1st recycle:

	tensile (kg)	tear (g)	brightness	opacity
	5.021	35.5	79.1	83.8
	6.059	36.5	79.9	86.2
	4.367	35.0	80.0	85.3
	4.861	37.5	80.5	86.1
	5.144	35.0	81.3	85.5
	4.935	38.5	80.5	85.9
	5.438	36.0	80.9	86.4
	4.883	42.5	79.3	84.8
	5.159		80.5	85.0
avg.	**5.096**	**37.06**	**80.22**	**85.44**
st. dev.	**0.463**	**2.51**	**0.72**	**0.83**

2nd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	6.816	35.5	74.1	83.4
	7.174	49.0	77.8	86.2
	6.947	30.0	78.3	86.3
	6.871	34.0	78.7	86.6
	5.803	43.5	78.7	86.1
	6.935	36.5	75.6	86.1
	4.982	40.0	77.4	87.1
	4.767	34.0	78.8	87.7
	7.470	37.0	75.1	87.1
avg.	**6.418**	**37.72**	**77.17**	**86.28**
st. dev.	**0.985**	**5.70**	**1.78**	**1.22**

3rd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	6.266	34.5	74.3	85.8
	7.080	30.0	74.9	85.4
	6.197	32.5	74.9	85.4
	8.000	33.0	74.3	86.3
	5.465	31.5	74.5	86.2
	6.942	34.0	74.4	86.1
	5.855	36.0	74.2	84.2
	6.518	34.5	72.2	83.7
	6.138		74.9	83.8
avg.	**6.496**	**33.25**	**74.29**	**85.21**
st. dev.	**0.754**	**1.91**	**0.83**	**1.04**

4th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	7.645	33.0	71.6	82.9
	7.672	38.0	72.4	81.9
	8.012	32.0	71.7	83.1
	7.887	34.0	71.2	81.4
	5.549	35.5	70.8	82.3
	5.144	34.4	70.5	82.4
	6.321	36.0	70.8	81.6
	6.671	35.5	70.6	80.5
			72.3	81.8
avg.	**6.863**	**34.80**	**71.32**	**81.99**
st. dev	**1.111**	**1.87**	**0.72**	**0.80**

5th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	7.270	38.0	68.3	81.2
	6.816	41.5	66.1	80.4
	5.460	39.0	68.9	81.5
	5.603	38.5	68.2	80.7
	6.497	37.0	68.6	81.9
	6.329	41.0	68.3	80.7
	6.947	39.0	68.8	79.6
	6.836	38.5	67.9	80.7
	6.472		68.9	80.0
			68.5	
avg.	**6.470**	**39.06**	**68.25**	**80.74**
st. dev.	**0.603**	**1.50**	**0.82**	**0.72**

Grade #2 - Cork Tipping

ranking amongst test grades (1=highest, 4=lowest)
% softwood - 2
degree of refining - 2
filler content - 1

1st recycle:

	tensile (kg)	tear (g)	brightness	opacity
	9.102	49.0	22.7	63.3
	8.930	49.5	22.7	62.8
	7.721	47.0	22.9	62.6
	7.445	55.0	22.7	62.9
	7.744	48.5	22.9	63.1
	6.979	50.0	22.8	63.1
	7.194	52.5	22.7	62.4
	7.862	49.5	22.6	62.9
	7.578		22.9	63.1
avg.	**7.839**	**50.13**	**22.77**	**62.91**
st. dev.	**0.724**	**2.50**	**0.11**	**0.28**

2nd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	8.730	52.5	23.5	63.1
	9.290	52.0	23.2	63.8
	7.679	44.5	23.1	63.3
	9.531	53.0	22.9	63.5
	8.528	54.0	23.4	64.0
	8.340	44.5	23.1	63.5
	8.429	44.0	23.4	63.8
	8.136	47.5	23.4	63.2
	8.575	47.0	23.0	63.2
avg.	**8.582**	**48.78**	**23.22**	**63.49**
st. dev.	**0.562**	**4.09**	**0.21**	**0.32**

3rd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	9.835	50.5	22.4	60.7
	8.878	49.5	22.3	60.3
	9.018	41.0	21.9	61.2
	9.016	42.0	21.7	61.0
	9.418	51.0	21.8	61.7
	9.413	40.5	22.1	61.3
	9.351	45.5	21.9	60.8
	9.408	43.0	22.4	60.8
	9.292		21.9	60.9
avg.	**9.292**	**45.38**	**22.04**	**60.97**
st. dev.	**0.288**	**4.39**	**0.27**	**0.40**

4th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	8.681	44.0	23.2	58.9
	8.338	61.0	22.8	58.7
	8.656	38.5	22.6	59.2
	8.843	45.0	22.4	59.4
	8.996	40.0	22.7	60.1
	7.544	50.0	22.4	59.9
	8.982	50.0	23.0	59.2
	9.206	45.5	23.0	59.4
	8.407		23.5	59.4
avg.	**8.628**	**46.75**	**22.84**	**59.36**
st. dev.	**0.494**	**7.07**	**0.37**	**0.44**

5th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	8.890	48.0	23.7	57.9
	9.236	46.0	23.7	58.2
	8.989	45.0	23.1	57.4
	8.466	46.5	24.1	56.4
	7.697	44.5	22.9	58.4
	9.689	45.0	22.7	58.7
	8.326	46.5	22.2	57.7
	8.207	47.0	22.8	57.5
	8.149		20.8	56.9
avg.	**8.628**	**46.06**	**22.84**	**57.68**
st. dev.	**0.621**	**1.18**	**0.94**	**0.73**

Grade #3 - Business Form

ranking amongst test grades (1=highest, 4=lowest)
% softwood - 4
degree of refining - 4
filler content - 2

1st recycle:

	tensile (kg)	tear (g)	brightness	opacity
	4.851	37.0	73.8	80.9
	4.912	32.5	74.6	78.7
	5.462	36.5	72.6	79.8
	5.721	31.0	74.4	80.2
	5.305	37.5	73.7	79.4
	5.011	35.0	72.8	78.3
	4.547	36.5	74.0	80.0
	4.496	35.5	73.6	79.9
	4.977		72.9	78.2
avg.	**5.031**	**35.19**	**73.60**	**79.49**
st. dev.	**.404**	**2.30**	**0.71**	**0.92**

2nd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	6.049	37.5	70.2	79.2
	5.425	36.5	70.9	80.7
	5.561	29.0	71.9	82.1
	5.354	34.0	72.1	81.4
	5.494	34.0	71.6	80.6
	5.783	31.0	71.4	81.3
	5.527	33.5	71.8	81.4
	6.059	42.0	71.7	81.3
	6.022	44.0	71.4	80.7
avg.	**5.697**	**35.72**	**71.44**	**80.97**
st. dev.	**0.285**	**4.87**	**0.58**	**0.81**

3rd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	6.370	32.0	68.4	78.0
	6.316	43.0	68.6	77.7
	6.444	31.0	68.8	78.2
	6.540	39.0	68.8	78.9
	6.930	39.5	68.9	78.8
	6.607	31.0	69.2	78.7
	6.432	35.5	68.4	78.5
	5.840	36.0	69.2	77.1
	6.298		69.3	77.5
avg.	**6.420**	**35.88**	**68.84**	**78.16**
st. dev.	**0.290**	**4.41**	**0.34**	**0.63**

4th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	5.931	41.0	66.6	74.1
	4.755	33.0	67.1	74.4
	5.546	30.0	67.3	74.3
	6.027	35.0	67.2	78.6
	6.000	33.5	67.8	77.1
	5.689	32.5	67.8	77.5
	5.418	36.0	66.5	79.2
	4.478	34.0	67.0	78.7
	6.890		66.1	78.3
avg.	**5.637**	**34.38**	**67.04**	**76.91**
st. dev.	**0.718**	**3.22**	**0.57**	**2.08**

5th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	4.792	30.0	64.2	77.2
	6.165	29.0	64.6	78.4
	7.097	30.5	65.8	77.0
	6.207	28.5	64.8	77.0
	5.248	29.0	65.9	77.8
	5.739	29.5	65.9	77.7
	5.224	28.5	65.4	78.0
	5.083	30.0	66.1	75.4
	5.176		63.0	75.9
			65.6	
avg.	**5.631**	**29.38**	**65.13**	**77.12**
st. dev.	**0.733**	**0.74**	**0.98**	**0.96**

Grade #4 - Photographic Imaging

ranking amongst test grades (1=highest, 4=lowest)
% softwood - 4
degree of refining - 4
filler content - 2

1st recycle:

	tensile (kg)	tear (g)	brightness	opacity
	2.747	33.5	76.0	78.4
	2.644	32.5	76.1	79.5
	2.782	42.5	76.7	77.9
	2.969	38.5	76.2	79.2
	2.784	34.0	77.1	78.6
	2.809	36.5	76.4	78.4
	3.139	38.5	76.4	77.7
	2.930	40.0	76.3	79.0
	2.873		77.0	78.6
avg.	**2.853**	**37.0**	**76.47**	**78.59**
st. dev.	**0.145**	**3.49**	**0.39**	**0.58**

2nd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	6.575	31.5	71.7	81.2
	6.348	39.5	72.6	81.6
	7.388	39.0	72.9	81.4
	6.143	33.0	72.9	82.1
	6.491	47.0	72.9	82.3
	6.168	38.0	72.1	83.3
	5.926	34.0	73.2	81.8
	7.120	46.0	70.1	83.7
	6.871	36.5	73.4	83.1
avg.	**6.559**	**38.28**	**72.42**	**82.28**
st. dev.	**0.484**	**5.40**	**1.02**	**0.89**

3rd recycle:

	tensile (kg)	tear (g)	brightness	opacity
	5.748	37.5	70.5	76.5
	6.619	37.0	69.5	77.7
	7.277	31.5	71.1	78.0
	7.260	36.0	70.5	78.3
	7.317	41.0	70.8	77.5
	5.869	36.0	73.6	78.8
	5.933	34.5	69.7	77.5
	6.207	35.0	69.4	76.9
	5.534		69.5	76.7
avg.	**6.418**	**36.06**	**70.51**	**77.54**
st. dev.	**0.716**	**2.72**	**1.32**	**0.76**

4th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	4.612	37.5	68.5	76.4
	5.615	37.0	68.5	75.6
	6.535	30.0	68.5	73.9
	5.588	37.5	68.6	76.3
	4.128	37.0	69.9	76.5
	5.492	30.0	68.9	77.5
	6.020	34.0	68.4	77.7
	5.388	34.5	68.5	77.7
	4.727		69.1	76.5
avg.	**5.345**	**34.69**	**68.77**	**76.46**
st. dev.	**0.744**	**3.18**	**0.482**	**1.20**

5th recycle:

	tensile (kg)	tear (g)	brightness	opacity
	4.106	31.5	67.4	77.6
	5.847	38.0	65.7	77.9
	6.589	33.0	67.4	76.3
	4.594	36.5	64.9	75.6
	4.853	35.0	64.2	72.0
	5.527	34.0	65.4	75.3
	6.412	36.0	67.0	77.5
	6.266	34.5	66.3	75.3
	4.607		66.0	73.0
			66.2	
avg.	**5.422**	**34.81**	**66.05**	**75.61**
st. dev.	**0.912**	**2.05**	**1.05**	**2.04**

appendix III - grade #1 handsheet samples

original sheet sample

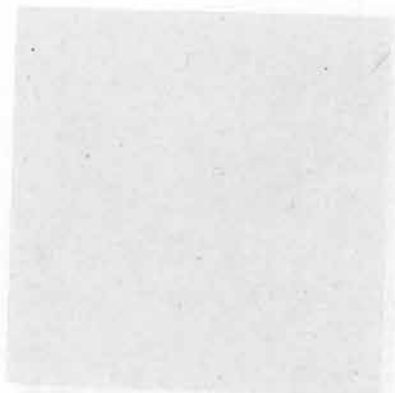
1st recycle

2nd recycle

3rd recycle

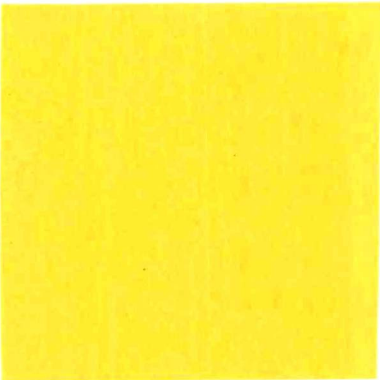
4th recycle

5th recycle



appendix IV - grade #2 handsheet samples

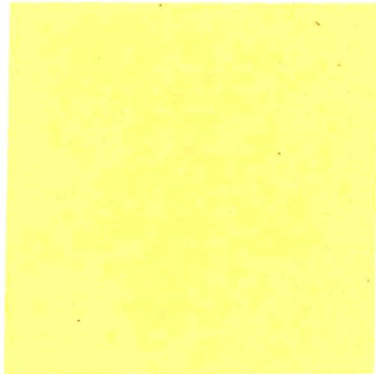
original sheet sample



1st recycle

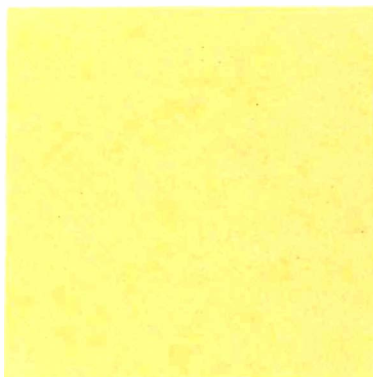
2nd recycle

3rd recycle



4th recycle

5th recycle



appendix V - grade #3 handsheet samples

original sheet sample

1st recycle

2nd recycle

3rd recycle

4th recycle

5th recycle

appendix VI - grade #4 handsheet samples

original sheet sample

1st recycle

2nd recycle

3rd recycle

4th recycle

5th recycle