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Application of Image Analysis to Recycled Fiber Characteristics

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APPLICATION OF IMAGE ANALYSIS TO RECYCLED FIBER CHARACTERISTICS

BY
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Student_________________________

Contents

Abstract

The purpose of this thesis was to determine if crimp could be measured in virgin and recycled Kraft softwood. Comparisons of the physical property data and the crimp values were also to be done.
The results for this thesis showed that crimp is not an important property of the softwood used. Because of this the comparisons of data could not be done. More research must be done to determine if the sampling methods that used are valid and if crimp can be found in other fiber types.

Keywords:

Image Analysis, Crimp, Softwood, Kraft, recycling, secondary fiber, physical paper property, geometric properties.

Introduction

The purpose of this thesis is to determine if crimp can be accurately and reliably measured in natural wood using image analysis. The second goal of this thesis is to determine if and how recycling will change the crimp of the fibers. The third goal was to look for correlation between crimp and the papers physical properties. Finally, was to record the new laboratory techniques that were developed.

Background

Computerized image analysis is still an open technique that has not yet reached its full capabilities in the area of data manipulation and hardware. New uses are still being found. The systems that are available are still mostly semi automatic systems that require the careful preparation of the samples to be analyzed. These systems allow many different and accurate measurements to be taken simultaneously, decreasing the measurement time from hours to minutes in some cases. Because of this ability to do so many repetitive measurements, image analysis has found use in measuring different size and geometrical properties of contaminants in recycled paper.

The image analysis system will be used in this thesis for all optical measurements. It measures the properties in question by differentiating between the gray level, which is the amount of reflected or transmitted light, of the image and its background. So by looking at the different contrast levels of the image, individual features can be selected and measured. The computer divides the gray levels into individual mathematical points which can then be used in the calculations selected by the program. This is done using a Vidicon tube located inside a video camera set above the specimen being measured. The size of the feature that can be detected by the camera is dependant on the lens, any extenders, and the distance the camera is above the sample. These variables also affect the area of image that can be measured each time. Because of this the frame size can be adjusted to include only the fibers that are of current interest[1]. This should be done and set before the image analyzer is calibrated.

A shading corrector is used to adjust for any curvature of the lens, variation in illuminations, or variations in the response of the scanner or video camera. It also calibrates the optical and video systems to a known black and white level[1].

The stage on which the sample is placed has two sources of lighting, reflected and transmitted. The type of lighting used depends on the task the operator has to perform.

The study of contaminants is useful and important to producing quality paper[2]. However, it is also important to look at the recycled fibers themselves to determine the quality of paper that can be produced. The fibers change physically as they are recycled and these changes can be viewed optically. Properties such as fiber size, curl, and crimp are reported by Graminski and Russel[3] to be measureable by image analysis. However, the physical techniques for this measurement are not yet clearly defined. One of the goals of this thesis is to determine how reliably these properties can be measured and if they can be correlated quantitatively to any other paper strength property.

Theoretical

This thesis will be an analysis of how wood fibers change physically as they are subjected to recycling. Initially virgin pulp will be used for the machine run. The changes in crimp in the fibers will be measured with an image analysis system similar to one discussed by Taylor and Dixon[4]. The purpose of doing this measurement is to determine if the image analyzer will produce reproducible and comparable results. If this is true, it may be possible to predict the increase or decrease of sheet strength. The paper produced on both machine runs will also be tested to determine the standard strength properties for comparison to the analyzer data. It is hoped that a valid correlation between values for crimp and the individual strength properties can be found,

Crimp is defined in general terms as the waviness of a fiber, a measure of the difference between the length of the unstraightened and the straightened fiber[5]. The computer measures crimp by looking at the fiber as a series of mathematical points taken at intervals along the detected length of the fiber. This definition however is not good enough for a quantitative analysis of crimp. So the computer uses a more technical definition.

Crimp is defined as a morphological substructure of a fiber which is V shaped and makes a transition from a high point to a low point, and another transtion back to a high point. Two factors must be specified for the transition parameter to be of use to the computer. They are the crimp amplitude exclusion factor and leg length exclusion factor. These two parameters set the minimum size for the crimps that will be measured. The following transformations are done by the image analyzer in order to measure the crimp in a fiber sample[6]. First, a grey level image is acquired and run-length encoded. Second, the features in the image are segmented and skeletonized. Which means that the overall image is broken into sections so that the computer capacity is not overloaded. The fibers are thin enough that one edge can be used as a representation for the whole fiber. Third, the starting and ending points of each segment are found. The computer now has a list of 1-dimensional linked points that forms an idealized skeleton of the fibers. Fourth, the list of points is examined and the inflection points are found, by the criteria listed in the definition. There is no need for the fibers to be orientated with the X-axis only that there be some change in the Y direction. Finally, the crimp legs are sorted by morphology into crimps and non-crimps which are then used in the measurements that are selected.

The conclusions that will be looked for in this thesis will be from three major points. The first point is if crimp can be measeured in nature fibers and if the data is reliable. The second point is if there are any detectable changes in the crimp during the recycling process. The final point is to see if there is any comparison between crimp and the paper samples physical properties.

Experimental Plan

Materials

The materials needed for this thesis are nonspecialized in nature. The only major stock material requirement is 400 dry/lbs of softwood from the stock of the pilot plant. Some general laboratory supplies and 5 liters of deionized water.

Equipment

The use of the WMU pilot plant paper machine and attached equipment will be needed on two separate occasions for one half day in order to produce the needed paper samples (see below). The other equipment needed for this thesis is the student paper testing laboratory, the scanning electron microscope, and the image analyzer.

Procedure

The experimental plan for this thesis is broken into two portions: production of pulp and paper samples and the evaluation of those samples. The laboratory procedures for sample generation will be covered first.

This thesis requires that two machine runs be completed to produce the samples required for evaluation in the laboratory. The machine conditions for both trial runs must be held constant with the only variations being made in the pulp freeness and machine pH. The Table below shows the necessary macine conditions for the first run. The amount of stock used for the first run will be 400 dry/lbs total. This stock will be made up of all softwood in order to reduce the variation in stock properties. The only condition to be changed on the machine is the pH. The first half of the stock will be run under neutral to alkaline pH. The other half of the stock will be run at a pH of 4.5 to produce acid paper conditions.

The second trial run is a recycling of the paper produced in the first run. The stock dispersion is done in the hydrapulper with the pH adjusted to 9. After dispersal the stock will be pumped to the machine chest and run under the same machine conditions as the first run.

Machine Conditions for Paper Trials

	Standard	Average
Pulp Furnish	100% softwood	
Water	100 ppm $CaCO_3$	
Refiner type	Double disc	
Target freeness (csf)	450	456
Basis weight (lbs/3000 ft². - 500 sheets)	40	35.818
Machine Speed (ft/min)	88	89.4
Production rate (lbs/hi)	160	160
Two wet presses (psi each)	40	40
Drying (steam pressure)		
First section	5 (psi)	
Second section	2 (psi)	
Machine calendar	1 nip	
Moisture at reel	4%	3.85%
Trim at reel	22"	
Tray water pH	7,4	8.13, 4.7

The samples taken from each of the machine runs are listed in the following table. These samples are from the machine and stock preparation part of the experiment.

Required Machine Samples

First Machine Run

1. Stock chest before refining------------------ 2 liter
2. Canadian Standard Freeness before refining
3. Stock chest after refining------------------ 2 liters
4. Final Canadian Standard Freeness
5. Headbox samples for both pH levels---------- 1 liter each
6. Paper samples from both pH levels, after drying
   a. samples for physical property tests.
   b. samples for image analysis.

Second Machine Run (recycled fiber)

1. Sample from Hydrapulper (9pH)--------------- 2 liters
2. Canadian Standard Freeness (hydrapulper)
3. Headbox samples for both pH ---------------- 1 liter
4. Paper samples as above.

The laboratory part of the thesis will consist of image analysis and physical property testing. The image analysis portion of the laboratory procedure will be done on the departments image analysis system[1].

Samples of never dried and dried fibers from machine runs will be measured to determine crimp values for the fibers.

The image analyzer will be set up with an optical microscope to permit measurement of individual fibers from the samples. The video camera is mounted on top of the microscope and gives a direct magnified image of the fiber sample. With this setup it is possible to calibrate the image analyzer using the standard rules supplied by the manufacturer. From the samples listed above, portions will be diluted in deionized water and placed on slides for measurement. There were two methods of slide preparation that performed during this thesis. This was done due to the difficulties of producing clear images. The first method used slides with a depression in the center of the slide. This depression is designed to hold the fibers in a water film. The fibers were placed in the well on the slide by eydropper. Dye was then added to the water film on the slide. The dyes tried for this were methyl blue, C-stain, and Phenyl sky blue.This method produced poor images because the added dye made the water film a uniform color which in turn produce a uniform gray level image. Next, the fiber solution was dyed and rinsed before placement in the slide well. This method produced a clear image but the fibers were still to transparent to produce the neccessary difference in contrast to be measurable features. This method was also tried with methyl blue, C-stain, and Phenyl sky blue. Because of the imaging problems associated with the fiber suspension it was decided that the fibers would be dried on the surface of normal slides first. Drying the fibers would increase their opacity and make it easier to find and dye or stain that would make the fibers opaque. This was done for all the sample batches. When the fibers were stained and placed under the microscope the images that were produced were clear and had enough contrast to measure. The stain used on the fibers was C-stain. This turned the bleached kraft softwood of the samples a deep violet to a balck color which stood out clearly as features against the white background being used. This stain did not work well in solution because it will not fix primarily on the fibers but will be diluted by the water present reducing its effectivness.

The measurements were conducted on different fiber samples until significant data has been collected for each group. The measurement for crimp will be done for all the samples in the list above. Once the data has been collected and analyzed statistically it will be compared with the physical test results to look for any correlations between the results. The image analyzer is capable of simple statistical distribution and averaging functions. These will be used to look at the data.

Physical property tests for Tensile, Tear, Mullen, and Taber stiffness will be performed on the paper produced after each run. Standard TAPPI procedures will be followed for these tests. There will be no variations in the methods outlined by the standards.

Results

The results of this thesis, due to the small amount of crimp present in the samples, could not be presented in any type of summary form. The samples for the first run virgin pulp and the first run acid head box samples did not show crimp results. The raw data is presented in appendix 1, in tabular form as presented by the image analyzer. Appendix 2 contains a sample of the distribution range table and distribution histogram that the program produced.
The raw data for this thesis was taken in millimeters or micrometers, and each table reports the units that were used.

Discussion

The first point that this thesis examined was whether crimp was a measurable property of the natural softwood fibers used and if these numbers where valid. From the results that were collected, (see appendix 1) crimp was found to be measurable for all but the virgin pulp and the first run headbox samples. The values for the crimp, at the time of measurement, when compared to the visual image showed that the crimps were due to the bends in the fibers and not to fibers crossing. The computer is some what smart so that it can determine the presence of a crossing for a simple image. The results also show that the crimp, while present in the samples, is not a significant property. There was a range between 0 and 9 crimps per sample with the average being 3. These numbers are too low to be of use without having to make many measurements to get a statistical representation of the sample. Also, the crimps that were found tended to have open angles greater that 90°. This is an indication that the crimps present are of a natural origin and were not induced during the recycling process. Visual inspection of the sample images showed that the fibers were either linear or gently curving. There were very few of the transitions which are needed to define crimp. Sharper crimps are expected for the paper making and recycling process because of the amount of refining and shear stresses that the fibers would be subject to.

There are several possible reasons for why crimp was not found in significant amounts in the samples. The first possiblility is that the softwood Kraft that was used for the recycling was not a good model for actual recycled fibers. To simulate the process more accurately, the fibers may need a second refining. Second, the fibers were stored at a lower temperature which may have caused the fibers to relax to some extent and lose the sharper crimps. Third, the sampling methods used in this thesis could have altered the values for the fiber crimp. If a good dark fixed dye is found, a comparison of the wet slide and dry slide methods should be done. The final reason is that the softwood fibers naturally don't exhibit crimp under normal paper making conditions. This should be verified by comparison to other types of natural fiber.

The reasons that are most likely are the third and fourth ones. The way the samples were prepared and the softwood studied may not be the ideal system to use. More attention should have been put into the making of the slides to insure that the fiber geometry did not get radically altered. Also the softwood should have been refined again during the recycling to more accurately represent the wair fibers may experience.

The secondary goals of the thesis were not completed due to the lack of crimp data for comparison to the the physical properties of the paper produced (see appendix 3). There was not enough data for comparing the crimp values between the virgin paper run and the recycled run.

The sample preparation techniques that were used are recorded in the experimental section of this paper. These were the only methods that were attempted.

There was one major problem that fore-shortened this thesis, the image analyzer suffered from mechanical difficulties. This cut two weeks of research time from this thesis while the analyzer was repaired, and this wait caused a crowding of people using the analyzer. Because of this, it was only possible to run a minimum of samples for each person. With more avaible time it should be possible to answer more of the questions raised.

Conclusions

This thesis really raised many more questions than it answered. More reasearch has to be done to determine which is the best image sampling technique to use. Also it must verified if that the softwood used was a good model for the comparisons that were orignalily planned.

It was determined that crimp is present in the softwood samples that were used in this thesis. However crimp was not present in large enough quantities to be considered a significant property for the softwood used. The other goals were not answered due to lack of data.

Recommendations

It was also concluded that more research must be done with the sample preparation to make sure that the methods used don't alter the results. Also, other types of fibers must be measured to see if crimp is a significant property in any natural fiber. If crimp is found, then the other goals of this thesis should be attempted.

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Notes

1. The image analyzer used in this thesis is produced by Arteck Inc and is name the Omnicron 3000 Image Analysis system.

APPENDIX 1

This appendix contains the results for the samples measured. The results are presented in the form that the image analyzer produces. The standard deviation and ranges are calculated by the computer. The following list is the what the names of each sample mean.

Sample	Name
Vr	Virgin refinned pulp
HBALK1	Head box Alkaline range first run
HBAC1	Head box Acid range first run
ALK1P	Alkaline paper first run
ACID1	Acid paper first run
RP	Recycled pulp pH 9
HBALK2	Head box Alkaline range second run
HBAC2	Head box Acid range second run
ALK2P	Alkaline paper second run
ACID2P	Acid paper second run

OMNICON FibeMEASUREMENT REPORT
12:32 P.M. on Wed., Apr. 5, 1989
Calibration : 1x 1.3873E+02 µm²/pp
alk1p

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	10356.572	4338.010	5347.504	12877.069	7529.564
Relaxed Length	6846.472	2277.679	4246.990	8492.397	4245.408
Non-Crimp Distance	83.168	116.180	0.000	215.912	215.912
Percent Crimp	31.298	9.686	20.580	39.427	18.847
Crimps Per U.M.R.	0.003	0.000	0.002	0.003	0.000
Leg Length	282.797	34.630	243.068	306.597	63.528
Leg Amplitude	142.749	34.425	115.624	181.475	65.852
Percent Non-Crimp	0.647	0.905	0.000	1.681	1.681
Crimp Open Angle	97.201	18.838	84.540	118.850	34.310
Crimps Per U.M.S.	0.002	0.000	0.002	0.002	0.000
Relaxed/Stretched	0.687	0.097	0.606	0.794	0.188
Crimp Sharpness	336.719	200.987	197.434	567.127	369.693

Number of features = 3
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
12:59 P.M. on Wed., Apr. 5, 1989
Calibration : 1x 1.3873E+02 µm²/pp
acid2p

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	6499.781	3713.586	2506.783	9850.051	7343.268
Relaxed Length	4028.680	2414.879	1688.004	6511.484	4823.481
Non-Crimp Distance	193.429	296.991	0.000	535.383	535.383
Percent Crimp	37.381	7.132	32.663	45.586	12.923
Crimps Per U.M.R.	0.002	0.001	0.002	0.003	0.001
Leg Length	359.692	49.956	310.544	410.419	99.875
Leg Amplitude	146.180	80.766	54.134	205.197	151.063
Percent Non-Crimp	7.329	12.153	0.000	21.357	21.357
Crimp Open Angle	68.514	42.727	20.995	103.765	82.771
Crimps Per U.M.S.	0.001	0.000	0.001	0.002	0.000
Relaxed/Stretched	0.626	0.071	0.544	0.673	0.129
Crimp Sharpness	191.397	173.003	53.363	385.474	332.110

Number of features = 3
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
2:37 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm²/pp
HBALK2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	6.589	5.247	2.879	10.299	7.420
Relaxed Length	3.674	1.848	2.367	4.981	2.614
Non-Crimp Distance	0.173	0.244	0.000	0.346	0.346
Percent Crimp	34.721	23.932	17.798	51.643	33.845
Crimps Per U.M.R.	2.673	0.195	2.535	2.811	0.276
Leg Length	0.295	0.104	0.221	0.368	0.146
Leg Amplitude	0.161	0.101	0.089	0.232	0.143
Percent Non-Crimp	6.001	8.486	0.000	12.001	12.001
Crimp Open Angle	105.335	26.099	86.880	123.789	36.909
Crimps Per U.M.S.	1.722	0.512	1.359	2.084	0.725
Relaxed/Stretched	0.653	0.239	0.484	0.822	0.338
Crimp Sharpness	0.167	0.078	0.112	0.222	0.110

Number of features = 2
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
1:21 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm²/pp
HBAC2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	7.561	4.549	4.084	13.664	9.580
Relaxed Length	4.977	3.266	2.387	9.210	6.823
Non-Crimp Distance	0.583	0.492	0.045	1.200	1.155
Percent Crimp	36.232	5.847	29.932	41.551	11.620
Crimps Per U.M.R.	3.497	0.387	2.932	3.771	0.839
Leg Length	0.198	0.020	0.168	0.215	0.047
Leg Amplitude	0.083	0.015	0.061	0.093	0.033
Percent Non-Crimp	10.037	12.984	1.103	29.327	28.224
Crimp Open Angle	88.672	10.729	78.392	102.801	24.410
Crimps Per U.M.S.	2.219	0.214	1.976	2.498	0.522
Relaxed/Stretched	0.638	0.058	0.584	0.701	0.116
Crimp Sharpness	0.330	0.310	0.113	0.788	0.675

Number of features = 4
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
12:33 P.M. on Thurs., Mar. 30, 1989
Calibration : 1x 2.6806E+04 µm²/pp
acid1

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	48551.646	28529.896	20300.515	106741.800	86441.285
Relaxed Length	36087.535	19889.596	19130.982	79917.267	60786.285
Non-Crimp Distance	2398.224	3693.744	0.000	9507.210	9507.210
Percent Crimp	20.670	16.506	1.079	50.391	49.312
Crimps Per U.M.R.	0.000	0.000	0.000	0.000	0.000
Leg Length	2207.066	756.021	1127.806	3092.413	1964.607
Leg Amplitude	845.800	640.400	229.012	2156.466	1927.455
Percent Non-Crimp	7.267	12.730	0.000	37.308	37.308
Crimp Open Angle	109.102	27.056	84.898	167.862	82.964
Crimps Per U.M.S.	0.000	0.000	0.000	0.000	0.000
Relaxed/Stretched	0.793	0.165	0.496	0.989	0.493
Crimp Sharpness	6449.172	4744.981	1058.365	11824.546	10766.181

Number of features = 9
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
3:24 P.M. on Thurs., Mar. 30, 1989
Calibration : 1x 2.6806E+04 µm²/pp
acid2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	62952.751	40660.595	23844.603	121241.686	97397.083
Relaxed Length	56165.630	38263.715	21587.362	108856.792	87269.430
Non-Crimp Distance	5733.866	4984.825	0.000	10717.183	10717.183
Percent Crimp	10.804	13.269	0.462	33.062	32.601
Crimps Per U.M.R.	0.000	0.000	0.000	0.001	0.000
Leg Length	1365.521	196.179	1131.528	1589.640	458.112
Leg Amplitude	229.984	205.076	64.668	565.405	500.737
Percent Non-Crimp	17.604	21.373	0.000	44.946	44.946
Crimp Open Angle	117.527	27.366	88.547	161.299	72.753
Crimps Per U.M.S.	0.000	0.000	0.000	0.000	0.000
Relaxed/Stretched	0.892	0.133	0.669	0.995	0.326
Crimp Sharpness	11483.143	8266.598	3164.865	21282.705	18117.840

Number of features = 5
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
1:01 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm²/pp
HBAC2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	5.766	1.430	4.237	7.627	3.390
Relaxed Length	3.799	2.260	1.912	6.851	4.939
Non-Crimp Distance	0.956	1.106	0.000	1.987	1.987
Percent Crimp	37.981	22.038	10.178	56.451	46.273
Crimps Per U.M.R.	1.208	1.054	0.146	2.406	2.260
Leg Length	1.138	0.986	0.299	2.542	2.244
Leg Amplitude	0.413	0.430	0.010	0.962	0.951
Percent Non-Crimp	17.751	22.507	0.000	46.888	46.888
Crimp Open Angle	51.862	43.955	1.086	97.644	96.558
Crimps Per U.M.S.	0.702	0.705	0.131	1.674	1.543
Relaxed/Stretched	0.620	0.220	0.435	0.898	0.463
Crimp Sharpness	2.229	3.016	0.053	6.454	6.401

Number of features = 4
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
1:35 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm²/pp
HBAC2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	13.931	8.286	8.072	19.790	11.718
Relaxed Length	8.230	3.943	5.442	11.019	5.576
Non-Crimp Distance	0.133	0.018	0.120	0.146	0.026
Percent Crimp	38.450	8.303	32.579	44.321	11.743
Crimps Per U.M.R.	2.829	0.363	2.572	3.086	0.513
Leg Length	0.276	0.010	0.269	0.283	0.014
Leg Amplitude	0.135	0.011	0.127	0.143	0.016
Percent Non-Crimp	1.113	0.531	0.737	1.489	0.751
Crimp Open Angle	95.859	7.060	90.866	100.851	9.985
Crimps Per U.M.S.	1.726	0.012	1.718	1.734	0.016
Relaxed/Stretched	0.616	0.083	0.557	0.674	0.117
Crimp Sharpness	0.168	0.138	0.070	0.265	0.195

Number of features = 2
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
11:25 A.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7712E-04 mm^2/pp
RP1

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	1.569	0.000	1.569	1.569	0.000
Relaxed Length	1.556	0.000	1.556	1.556	0.000
Non-Crimp Distance	0.764	0.000	0.764	0.764	0.000
Percent Crimp	0.852	0.000	0.852	0.852	0.000
Crimps Per U.M.R.	3.214	0.000	3.214	3.214	0.000
Leg Length	0.065	0.000	0.065	0.065	0.000
Leg Amplitude	0.002	0.000	0.002	0.002	0.000
Percent Non-Crimp	48.693	0.000	48.693	48.693	0.000
Crimp Open Angle	104.423	0.000	104.423	104.423	0.000
Crimps Per U.M.S.	3.186	0.000	3.186	3.186	0.000
Relaxed/Stretched	0.991	0.000	0.991	0.991	0.000
Crimp Sharpness	1.242	0.000	1.242	1.242	0.000

Number of features = 1
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
11:39 A.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7712E-04 mm^2/pp
RP

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	2.770	0.000	2.770	2.770	0.000
Relaxed Length	1.804	0.000	1.804	1.804	0.000
Non-Crimp Distance	1.169	0.000	1.169	1.169	0.000
Percent Crimp	34.870	0.000	34.870	34.870	0.000
Crimps Per U.M.R.	1.109	0.000	1.109	1.109	0.000
Leg Length	0.308	0.000	0.308	0.308	0.000
Leg Amplitude	0.131	0.000	0.131	0.131	0.000
Percent Non-Crimp	42.219	0.000	42.219	42.219	0.000
Crimp Open Angle	105.450	0.000	105.450	105.450	0.000
Crimps Per U.M.S.	0.722	0.000	0.722	0.722	0.000
Relaxed/Stretched	0.651	0.000	0.651	0.651	0.000
Crimp Sharpness	0.063	0.000	0.063	0.063	0.000

Number of features = 1
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
12:10 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm^2/pp
RP

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	8.412	0.745	7.886	8.939	1.054
Relaxed Length	5.659	1.331	4.718	6.600	1.882
Non-Crimp Distance	0.254	0.205	0.109	0.399	0.290
Percent Crimp	33.172	9.901	26.171	40.173	14.002
Crimps Per U.M.R.	4.725	1.111	3.940	5.511	1.572
Leg Length	0.154	0.012	0.146	0.163	0.017
Leg Amplitude	0.066	0.007	0.061	0.071	0.010
Percent Non-Crimp	2.927	2.175	1.388	4.465	3.077
Crimp Open Angle	95.664	3.257	93.361	97.967	4.606
Crimps Per U.M.S.	3.103	0.275	2.909	3.297	0.389
Relaxed/Stretched	0.668	0.099	0.598	0.738	0.140
Crimp Sharpness	0.114	0.007	0.109	0.119	0.009

Number of features = 2
Number of fields = 1

1:26 P.M. on Wed., Apr. 5, 1989
Calibration : 1x 1.3873E+02 µm²/pp
hbalk1

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	1963.497	168.328	1844.472	2082.523	238.052
Relaxed Length	1736.217	296.851	1526.312	1946.122	419.810
Non-Crimp Distance	109.867	155.375	0.000	219.733	219.733
Percent Crimp	11.900	7.566	6.550	17.249	10.700
Crimps Per U.M.R.	0.004	0.001	0.003	0.005	0.002
Leg Length	144.412	41.199	115.279	173.544	58.264
Leg Amplitude	33.751	3.926	30.975	36.527	5.553
Percent Non-Crimp	5.957	8.424	0.000	11.913	11.913
Crimp Open Angle	110.382	14.049	100.448	120.317	19.869
Crimps Per U.M.S.	0.003	0.001	0.003	0.004	0.001
Relaxed/Stretched	0.881	0.076	0.828	0.935	0.107
Crimp Sharpness	768.820	798.485	204.206	1333.434	1129.228

Number of features = 2
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT

12:49 P.M. on Wed., Apr. 5, 1989
Calibration : 1x 1.3873E+02 µm²/pp
alk2p

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	2528.586	585.712	1682.782	3030.506	1347.723
Relaxed Length	2004.515	326.671	1615.143	2311.807	696.664
Non-Crimp Distance	0.000	0.000	0.000	0.000	0.000
Percent Crimp	18.917	12.703	4.020	32.148	28.128
Crimps Per U.M.R.	0.002	0.001	0.002	0.004	0.002
Leg Length	340.144	82.831	228.129	420.696	192.566
Leg Amplitude	101.324	34.441	55.229	133.740	78.510
Percent Non-Crimp	0.000	0.000	0.000	0.000	0.000
Crimp Open Angle	121.055	35.786	82.619	168.989	86.369
Crimps Per U.M.S.	0.002	0.001	0.001	0.003	0.001
Relaxed/Stretched	0.811	0.127	0.679	0.960	0.281
Crimp Sharpness	6113.271	11377.580	74.111	23170.692	23096.581

Number of features = 4
Number of fields = 1

OMNICON FibeMEASUREMENT REPORT
2:51 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm²/pp
HBALK2

CRIMP ANALYSIS

	MEAN	STD DEV	MIN	MAX	RANGE
Stretched Length	17.105	0.000	17.105	17.105	0.000
Relaxed Length	11.100	0.000	11.100	11.100	0.000
Non-Crimp Distance	0.657	0.000	0.657	0.657	0.000
Percent Crimp	35.107	0.000	35.107	35.107	0.000
Crimps Per U.M.R.	4.505	0.000	4.505	4.505	0.000
Leg Length	0.150	0.000	0.150	0.150	0.000
Leg Amplitude	0.077	0.000	0.077	0.077	0.000
Percent Non-Crimp	3.841	0.000	3.841	3.841	0.000
Crimp Open Angle	84.438	0.000	84.438	84.438	0.000
Crimps Per U.M.S.	2.923	0.000	2.923	2.923	0.000
Relaxed/Stretched	0.649	0.000	0.649	0.649	0.000
Crimp Sharpness	0.156	0.000	0.156	0.156	0.000

Number of features = 1
Number of fields = 1

APPENDIX 2

This appendix contains samples of the other tables produced by the image analyzer. These can be used along with the general statistics tables from appendix 1 to help determine the distribution of up to three specific properties. They were not used in this thesis do to lack of data to a significant distribution.

DISTRIBUTION ANALYSIS on Percent Crimp
UnderSize : 1
OverSize : 1

BIN	START	END	COUNT
1	26.307	26.307	0
2	26.307	26.307	0
3	26.307	26.307	0
4	26.307	26.307	0
5	26.307	26.307	0
6	26.307	26.307	0
7	26.307	26.307	0
8	26.307	26.307	0
9	26.307	26.307	0
10	26.307	26.307	0
11	26.307	26.307	0
12	26.307	26.307	0
13	26.307	26.307	0
14	26.307	26.307	0
15	26.307	26.307	0
16	26.307	26.307	0

BIN	START	END	COUNT
17	26.307	26.307	0
18	26.307	26.307	0
19	26.307	26.307	0
20	26.307	26.307	0

OMNICON FibeMEASUREMENT REPORT
2:37 P.M. on Sun., Mar. 26, 1989
Calibration : 1x 1.7446E-04 mm^2/pp
HBALK2

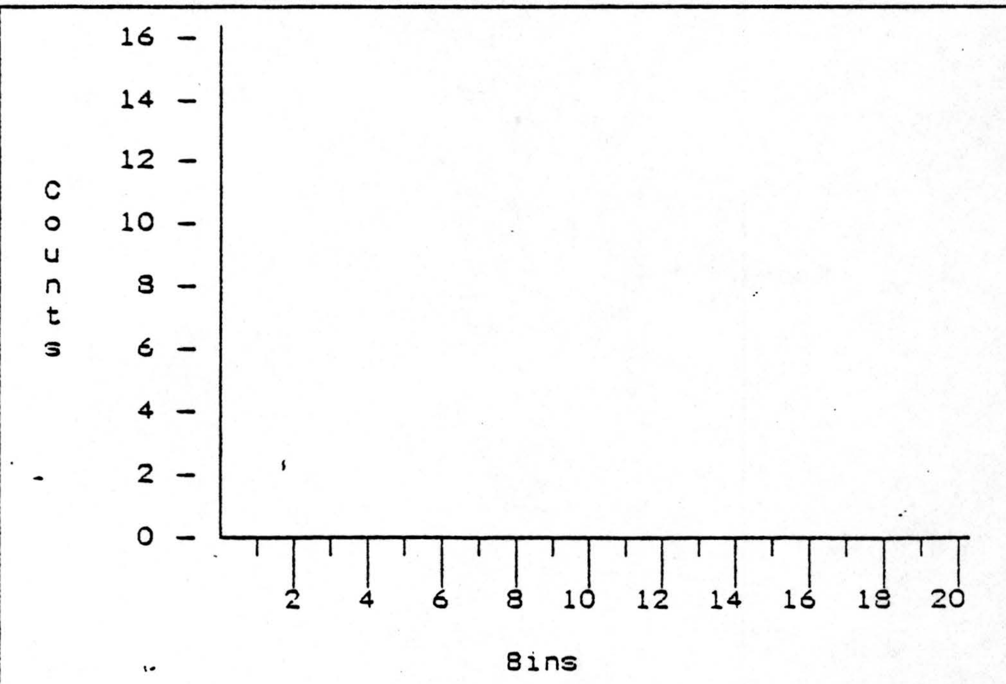
Frequency Histogram - HBALK2

Linear Distribution

Percent Crimp

Offset : 26.307
Size : 0.0
Range : 26.307
Under : 1
Over : 1

Cal. : mm



OMNICON Fibers II Version 1.34		Sun., Mar. 26, 1989
SAMPLE NAME: HBAC2 SETUP FILE: EVERT1		12:52:36 P.M.
VIDEO...... Auto White FREEZE............ on FILL-IN........... on DETECTION........ dark UPPER............. 250 LOWER............. 159 BRIGHTNESS........ 250 IMAGE DISPLAY... b & w VIDEO INPUT RATE 60 Hz FRAME........ variable ULC........ 20, 15 LRC........ 512, 430 OUTPUT DEVICES: Crt............. on Printer......... off Erosion Display Mode: 2	OPTICAL CALIBRATION: Objective......... 1x Units......... mm²/pixel Factor....... 1.7446E-04 PICKED FEATURES: picks cleared FRAME EXCLUSION: off NUMBER OF FIELDS..... 1 CURRENT FIELD........ 1 OUTPUT BETWEEN FIELDS. on CURRENT DIRECTORIES: Result Files. C:ÑFIBERS2 Image Files.. C:ÑFIBERS2 Setup Files.. C:ÑFIBERS2 Type any key to continue.	STATISTICS: on ANALYSIS: Crimp Crimp Ends: exclude Exclusions: Leg Length: 0.000 Leg Amplitude 0.000 DISTRIBUTION: 1 Non-Crimp Distance Size... 0.000 Offset... 0.000 DISTRIBUTION: 2 Crimp Sharpness Size... 0.000 Offset... 0.255 DISTRIBUTION: 3 Leg Length Size... 0.000 Offset... 0.314

APPENDIX 3

This appendix contains the physical property data for the paper produced in this thesis.

Second run Alkaline Paper

ROW	MDTENS.	CDTENS.	MDTEAR	CDTEAR	MULLEN	MULLENF	MDSTIFF	CDSTIFF
1	7.2	2.7	5.00	7.8	37.5	36.0	30.8	36.0
2	6.8	2.6	5.00	8.0	35.0	41.0	30.7	34.5
3	7.9	2.2	5.40	8.1	41.0	34.5	31.8	38.3
4	7.1	2.7	5.40	7.2	30.0	35.8	32.3	38.5
5	8.0	2.5	5.50	7.9	35.0	38.0	30.8	35.3
6	6.3	2.0	5.20	8.2	5.0	42.0	29.0	36.0
7	7.8	2.6	5.00	7.7	31.0	37.0	31.5	37.3
8	5.2	2.2	5.70	7.8	32.0	36.0	32.0	37.5
9	10.0	2.7	6.40	7.4	42.0	41.5	31.5	35.5
10	7.2	2.6	5.25	7.2	37.5	37.0	31.8	36.5
11	7.7	2.5	5.50	7.4	40.0	37.5	32.3	37.0
12	7.1	2.4	5.50	7.9	283.0	37.0	31.3	36.5
13	6.8	2.5	5.60	8.1	28.0	43.0	32.3	37.3
14	8.0	2.4	6.30	7.6	34.0	44.0	36.8	36.5
15	8.0	2.4	5.00	7.4	38.0		30.8	34.3
16	8.5				36.5		31.8	36.5
17							31.5	38.3
18							31.5	35.8
19							32.5	39.8
20							31.0	36.0

Second run Alkaline Paper

ROW	MDTENS.	CDTENS.	MDTEAR	CDTEAR	MULLEN	MULLENF	MDSTIFF	CDSTIFF
1	6.5	2.7	27.0	38.0	44.0	42.0	30.5	37.0
2	7.0	3.3	25.0	38.5	37.0	37.0	34.0	36.5
3	6.6	3.2	27.5	35.0	48.0	35.0	34.8	39.5
4	5.7	3.4	31.0	34.0	44.0	38.0	32.8	36.0
5	6.9	3.3	30.5	36.0	40.0	38.0	31.3	40.0
6	6.8	3.1	24.0	36.0	43.0	37.0	33.3	32.9
7	7.4	3.3	23.5	37.0	44.0	39.5	33.5	38.0
8	7.0	3.3	26.0	36.0	45.0	39.0	34.5	36.0
9	7.6	3.1	27.0	35.0	50.0	37.5	38.3	36.6
10	7.1	3.2	27.0	38.0	45.0	37.0	31.8	38.3
11	6.3	3.3	24.0	36.0	41.0	38.0	29.0	37.0
12	7.3	3.1	25.0	36.0	43.0	41.5	30.8	35.1
13	5.9	3.5	25.6	37.0	40.0	31.5	32.8	35.8
14	6.4	3.1	24.5	36.0	46.0	40.0	32.3	35.6
15	7.3	2.8	30.0	36.5	42.5	40.0	32.8	34.5
16	6.4		28.0	37.0			32.0	35.8
17	7.1						31.8	34.8
18							31.0	34.3
19							33.3	34.5
20							34.8	34.8

First run Alkaline Paper

ROW	MDTENS.	CDTENS.	MDTEAR	CDTEAR	MULLEN	MULLENF	MDSTIFF	CDSTIFF
1	6.8	9.2	4.33333	7.2	46.5	25.0	31.25	34.5
2	7.5	6.0	4.50000	5.0	46.5	38.0	31.50	34.3
3	6.3	6.2	5.00000	4.8	42.5	40.0	31.30	36.3
4	8.1	6.4	5.50000	4.9	42.0	45.0	32.00	34.8
5	6.8	6.0	5.16667	5.6	46.5	29.0	31.30	35.0
6	6.4	6.0	5.33333	5.8	44.0	39.0	32.80	36.0
7	7.0	6.4	5.00000	5.2	49.0	31.0	31.50	39.0
8	6.7	6.4	5.00000	5.2	49.5	36.0	31.30	35.0
9	8.4	7.0	5.33333	5.4	39.5	41.5	28.00	38.0
10	7.4	5.0	5.33333	6.0	43.0	47.5	30.00	37.8
11	6.4	4.8	6.00000	6.6	26.0	42.5	30.00	37.3
12	7.7	4.9	6.20000	6.2	47.0	39.5	31.80	32.8
13	7.4	5.6	6.40000	6.4	40.0	36.0	30.30	40.3
14	7.8	5.8	6.00000	6.0	51.0	45.5	31.00	34.0
15	6.7	5.2	6.40000	6.0	49.5	35.0	31.30	33.8
16	5.8	5.2	6.40000	6.4			31.30	34.3
17	7.1	5.4		6.4			30.30	36.0
18								33.0
19								34.0
20								33.0

First run Acid Paper

ROW	mdten	mdtear	cdtear	mullen	fmullen	cdten	mdstiff	cdstiff
1	6.9	5.33333	7.6	39.0	39.0	3.1	35.5	36.0
2	7.7	5.16667	7.2	38.5	35.0	2.7	35.3	35.3
3	5.7	5.08333	8.0	42.0	33.0	3.3	33.3	38.5
4	6.6	5.00000	6.6	43.0	39.5	2.4	31.0	37.3
5	7.4	5.00000	6.4	43.0	43.5	2.7	31.5	30.5
6	8.2	4.91667	6.9	41.0	44.0	2.4	33.0	35.8
7	6.7	6.25000	7.2	44.0	36.5	2.3	31.5	37.0
8	7.3	5.75000	7.8	37.0	39.5	2.6	32.8	37.8
9	6.6	5.41667	7.0	40.0	31.5	2.6	31.8	33.0
10	7.6	5.50000	7.5	42.0	38.0	3.3	30.8	34.3
11	7.9	5.83333	8.0	43.0		3.0	30.0	35.3
12	7.3	5.25000	7.8	40.0		3.1	31.3	34.5
13	8.1	5.75000	7.5	45.0		3.0	30.3	39.8
14	8.1	5.50000	7.4	33.0		2.4	32.3	37.3
15	8.6		8.3	41.0		2.8	32.0	36.8
16	8.2						32.0	36.8
17							29.8	35.8
18							33.3	32.5
19							32.0	33.3
20							31.0	37.3