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The Effect of Fines on the Surface Characteristics of Recycled Paper

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by

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ABSTRACT

With the steady increase in recycling comes an increasing need to understand the mechanisms involved with reused wood fibers. The purpose of this experiment is to determine the effects of fines on the surface characteristics of recycled paper, and to predict how an increase or decrease in fines loading might affect printing.

To meet these objectives, fines were removed from both virgin pulp and mill broke of similar composition. Each fines fraction was then reapplied to each long fraction at 0, 5, 10, and 15 percent loading by weight. British handsheets were made and evaluated for surface strength, absorbency, smoothness, and optical properties.

Fines from recycled stock were shown to be much less active than fines from virgin stock. Increasing recycled fines showed only a *very* slight improvement in surface strength, a reduction in liquid penetration, increased scattering/opacity, and slightly decreased brightness. No conclusions could be made for effects on smoothness. These results indicate that increased recycled fines would increase hold out and reduce ink penetration and ink show through.

Overall, with the exception of opacity, fines appear to play a much smaller role in paper making when the paper is recycled.

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INTRODUCTION

With the steady increase in recycling comes an increasing need to understand the mechanisms involved with reused wood fibers. The topic that was chosen will address a key question with recycled paper. When fibers are re-wetted and made into paper a second time or more, how does the increase in fines content affect the way the paper prints? Although the bulk properties of recycled papers have been measured and analyzed unto no end, from what could be concluded from the literature, far less research has been done in the areas of surface characteristics and fines influence. It is a known fact that the recycling process produces pulps with a higher fines content, especially when refining is involved. However, the recycling process can also cause a loss of fines during deinking, screening, and washing. It is also believed that in many cases, recycled paper prints better than comparable virgin paper. It is the intent of this project to determine how fines content affects the surface properties that influence printability of recycled papers.

Goals

The main goal of this project is to determine the affects that fines have on the surface characteristics of recycled paper, in order to give insight into predicting how increased recycled fines might affect the paper's print characteristics.

Objectives

In many cases recycled paper prints better than comparable virgin paper. The purpose of this research would be to tie in the level of fines in recycled paper, with the surface characteristics that affect printing, such as **surface strength** (as measured by wax pick and Scott Bond), **smoothness** (measured by Parker Print-Surf roughness, Parker compressibility, and Sheffield roughness), **absorbency** (determined by Parker porosity, the K&N ink test, and the T-432 test for water absorbency), and **optical properties** (such as opacity, scattering, and brightness). With these results for both virgin and secondary fiber, the fines' effect on printability will be discussed, related to ink hold out, strike-through, show through, ink absorbency, and surface bonding (related to linting, picking, and dusting). Although it can be theorized how fines might affect surface characteristics, it will be the intent of this research to help quantify these effects.

BACKGROUND

There have been numerous studies relating the effects of fines on strength properties, and a few have been written relating fines to surface properties. However, little information could be found that focused on how fines affect the surface properties of recycled paper.

Fines is a relative term, depending on how one defines it. TAPPI Provisional Method T261 pm-80 defines fines as the fiber fraction that will pass through a 200-mesh (76-micron) screen (Tibboles, page 8). It is well documented that increasing the level of fines in a virgin stock increases tensile, burst, and density, but there are mixed results in the area of opacity, brightness, and other surface properties.

Fines from secondary fiber, however, may or may not contribute to the strength of the sheet, depending on how these fines were generated. If the fines were generated during refining, they may be broken fiber fragments that could have broken off of hardened, brittle fibers. The fines could also have been formed during the original pulping or refining and were just carried over in the paper. In either case, the surface activity of the fines is probably much less than it was when the fines were in virgin form. Secondary fiber in general (from chemical pulps) show decreased density and strength, and increased opacity. This is because secondary fibers lose bonding potential with recycling due to hardening of the fiber surface and the loss of surface microfibrils. Also, and perhaps more prevalent, is the loss of relative bonded area due to a loss in fiber flexibility. The fibers are less compliable and tend to hold their rounded shape during pressing, while virgin fibers are more flexible and will flatten out to be more ribbon like, allowing for greater area of intersection between fibers.

When asked to describe *printability* and the factors affecting it, usually the first question raised is one of, "Well...that depends. For which printing process do you mean?" Before continuing, printability should be defined and the most popular printing methods should be discussed. Also, how increased secondary fiber generally affects printing should be discussed.

Printability is defined as the effect of the paper on the accuracy and precision of reproducing printed images (Smook, p.350). Generally, printability is most affected by smoothness, density, caliper, porosity, sizing, brightness, opacity, color, and gloss. How these factors affect the printability has a great deal to do with what printing method is used. Letterpress and flexography both use the relief method where raised surfaces covered with ink make an impression on the paper. Offset lithography uses the planographic method, where a plate covered roll transfers an ink image onto a rubber coated *blanket* roll. This blanket then transfers the image onto the paper. Lastly, the gravure method uses a chrome plated, copper roll covered with tiny engraved cells that make up the printed image. The roll rotates through an ink bath, followed by a doctor blade that removes the excess ink, and then the image is transferred to the paper (Smook, p.351). Each process uses a different method of ink transfer, as well as different types of ink, so each may require different levels of absorbtivity and smoothness. Also, each may or may not be sensitive to variations in density and caliper. Offset-litho and gravure are most sensitive to smoothness and density variations because they rely on a flat surface for transfer to occur evenly. Gravure needs a substrate that can pull the ink out of the cell on the plate, so a more absorbent sheet may be desirable. This property may not be desired with other processes, as in absorbency means less resistance to strike-through. Also, a low surface energy may be desired to limit wetting and bleeding on the surface.

How an ink transfers to the paper's surface is dictated by a number of factors. Good formation, low roughness, and consistent density and caliper are essential for uniform transfer of ink from the print roll, and therefore help to minimize print mottle. It is well known that recycled paper exhibits poorer bonding potential mainly due to the hornification process. These hardened fibers are much less flexible than virgin fibers, therefore roughness should increase and sheet density should decrease (for equal fiber lengths) adversely affecting printing (Jacobsson, p.2). This is also due to a decreased bonding potential. However, at the same time fibers tend be become shortened in the repulping process, especially when they are refined. This, along with increased levels of fines, may make the fiber network more dense and give it a smoother surface. The literature on this topic, however, shows mixed results.

Chatterjee found that recycled paper made from mechanical pulps tends to be more dense and smoother, while the opposite was seen for chemical pulps (p.133). In Jacobsson's thesis at Western Michigan University, using mixed waste (assuming 50/50 mechanical/chemical pulp), he showed that density stayed relatively constant and that roughness increased slightly, probably due to a mixture of chemical and mechanical pulps (Jacobsson, pp.9-11). Knight showed that floatation deinked fiber made paper with considerably higher roughness, probably due to loss of fines during the deinking process.

Porosity and density both affect absorbtivity of the ink into the sheet, and should therefore be especially important in gravure printing, where the capillary action of the paper must pull the ink out of the cells in minimal time. At the same time however, if density is too low or porosity is too high, then strike-through may be an undesired result. Smoothness must also be high, so as to make good contact with the ink in each cell. As previously stated, if the free surface energy is too high, then bleeding will occur, however if it is too low, then the ink will not wet the surface enough to be transferred. Recycled mechanical pulps tend to show a great decrease in porosity with recycling, while the porosity of chemical pulps tends to increase little if any (4%) (Chatterjee, p.130). The main conclusion to be drawn here is that secondary mechanical papers should show greater ink hold out and less strike-through than virgin papers. Secondary chemical papers on the other hand, should show a slight decrease in hold out and an increase in strike-through due to increased absorbtivity, as well as more spreading due to its higher free surface energy.

With increasing interest in the use of water based inks, it is becoming more important that printing papers become more dimensionally stable to water on the surface to prevent curl and cockle. Secondary fibers may be just right for this job. Due to hornification, especially with chemical pulps, the fibers should swell less and the paper should have higher dimensional stability (Chatterjee, p.133).

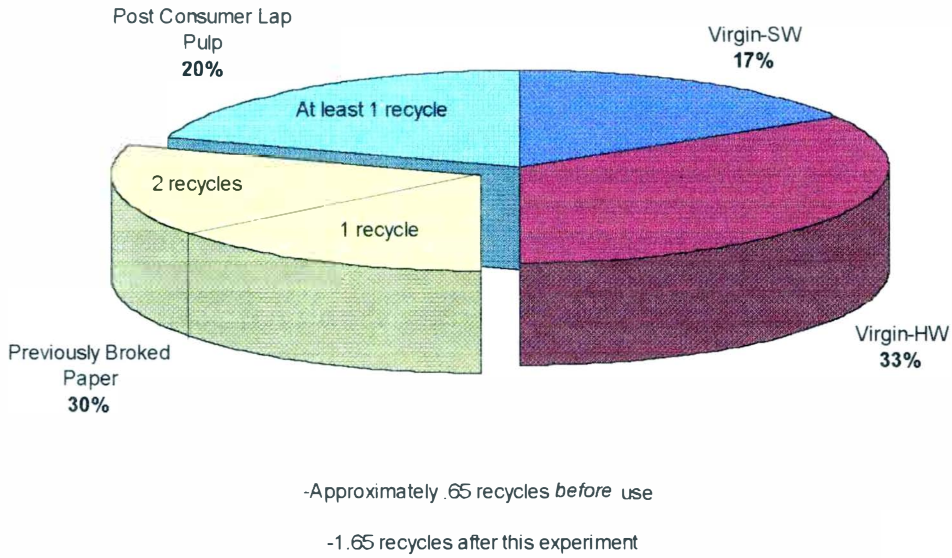
Internal bonding of the sheet is also an important factor in printing. The amount of linting, picking, dusting, and delamination occurs as a function of internal and surface bonding and as the result of tacky inks and shear development. Hipple showed that increasing the amount of secondary fiber to 75% (on virgin fiber) caused a 50% decrease in Mullen burst and Scott bond. It would be surprising if fines and their distribution did not play some role in the sheet's internal bonding. The increased tensile that is usually observed with increased fines indicates that their addition would probably help to raise this level of bonding.

EXPERIMENTAL PROCEDURE

Materials

The virgin stock consisted of a 50/50 blend of northern HW/SW dry lap pulp. This ratio was chosen to coincide with mill broke from a particular grade at Simpson Paper Company. This was a relatively low ash paper that was chosen to be used as the broked secondary fiber. This grade consists of 30% previously broked paper of the same grade and 20% deinked post consumer dry lap pulp. Therefore, 50% of the recycled paper that was used had already seen *at least* 1.3 recycles *before* this experiment. The remaining 50% of this paper was made with 67/33 HW/SW. The following chart illustrates the mill broke content more clearly:

Figure 1: Mill Broke Composition



A 50/50 HW/SW blend was chosen for the virgin stock so as to have an average blend or estimate of what the final broked paper might consist of.

Facilities and Equipment

Both the virgin fiber and the broke were provided by Simpson Paper Company in Vicksburg, Michigan. The Hydra-pulper, double disk refiner, the Sinclair Float Wash unit for fractionation, several stainless steel tanks for settling, an electronic tensile tester, a Parker porosity meter, and a brightness/opacimeter were provided by WMU's pilot plant. Other testing equipment, including a digital Scott internal bond measuring device, Parker

Print-Surf instrument, Sheffield roughness meter, K&N ink materials, an optical fiber length analyzer, and the British handsheet mold were provided by Simpson's Research & Development facility in Vicksburg, Michigan.

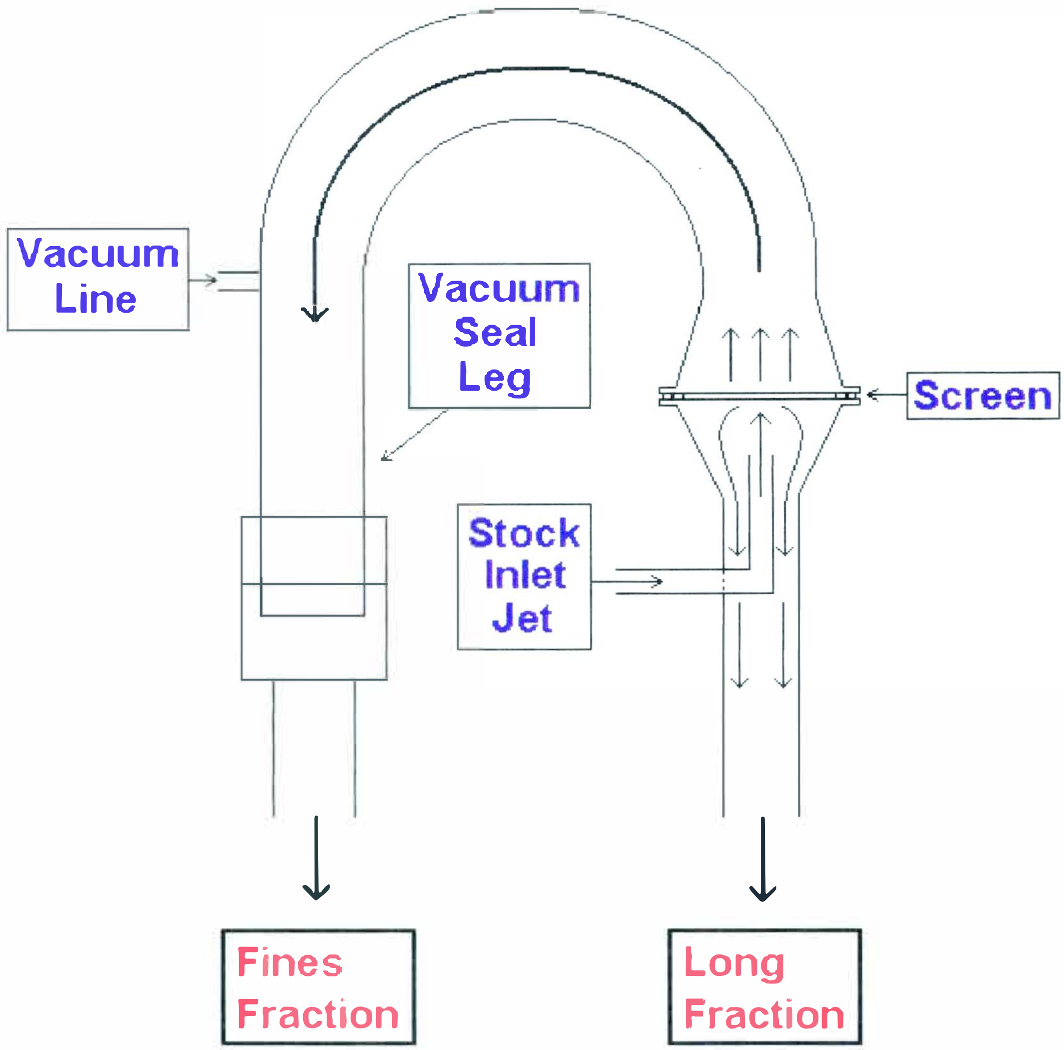
Methods

The basic procedure consists of pulping of the virgin fiber, repulping of the broke, fines fraction isolation of each, re-mixing of fines to the long fraction at varied levels (0-15%), handsheet production, and testing.

A 50/50 blend of HW/SW virgin, bleached kraft, dry lap pulp was slurried in the WMU Hydra-pulper and looped through the double disk refiner to 360 Canadian standard freeness (CSF). Separately, broked paper was pulped in the WMU hydropulper and refined to 360 CSF.

Each stock was then diluted to 0.25% consistency, followed by fines separation using the Sinclair Float Wash Unit equipped with a 150 mesh screen. The following is a diagram of the Sinclair Float Wash Unit:

Figure 2: Sinclair Float Wash Unit



Each fraction was placed in separate tanks, and after allowing enough time for each fraction to settle, an ample amount of the fines fraction was drained from each containment and placed in separate 50 gallon drums. The fines were allowed to settle for three days and water was then siphoned off the top of each drum in order to get each slurry to a manageable consistency. The thickened fines were then placed in several five gallon buckets for transport.

The long fraction was collected by draining the settled fibers into a pillow case. Several pillow cases full were dumped into several five gallon buckets for transport, along with the collected fines fractions, to Simpson Paper Company in Vicksburg.

At Simpson, each fraction was tested for consistency and fiber length on the Andridch Sprout-Bouer Fibre Scan optical fiber length analyzer. The fines fraction was then reapplied to the long fraction at varied levels: 0%, 5%, 10%, and 15% addition by weight. Each mixture was run through a TAPPI desentegrater for 8000 revolutions to ensure proper dispersion. Handsheets were then made using the British sheet mold equipped with a 150 mesh screen.

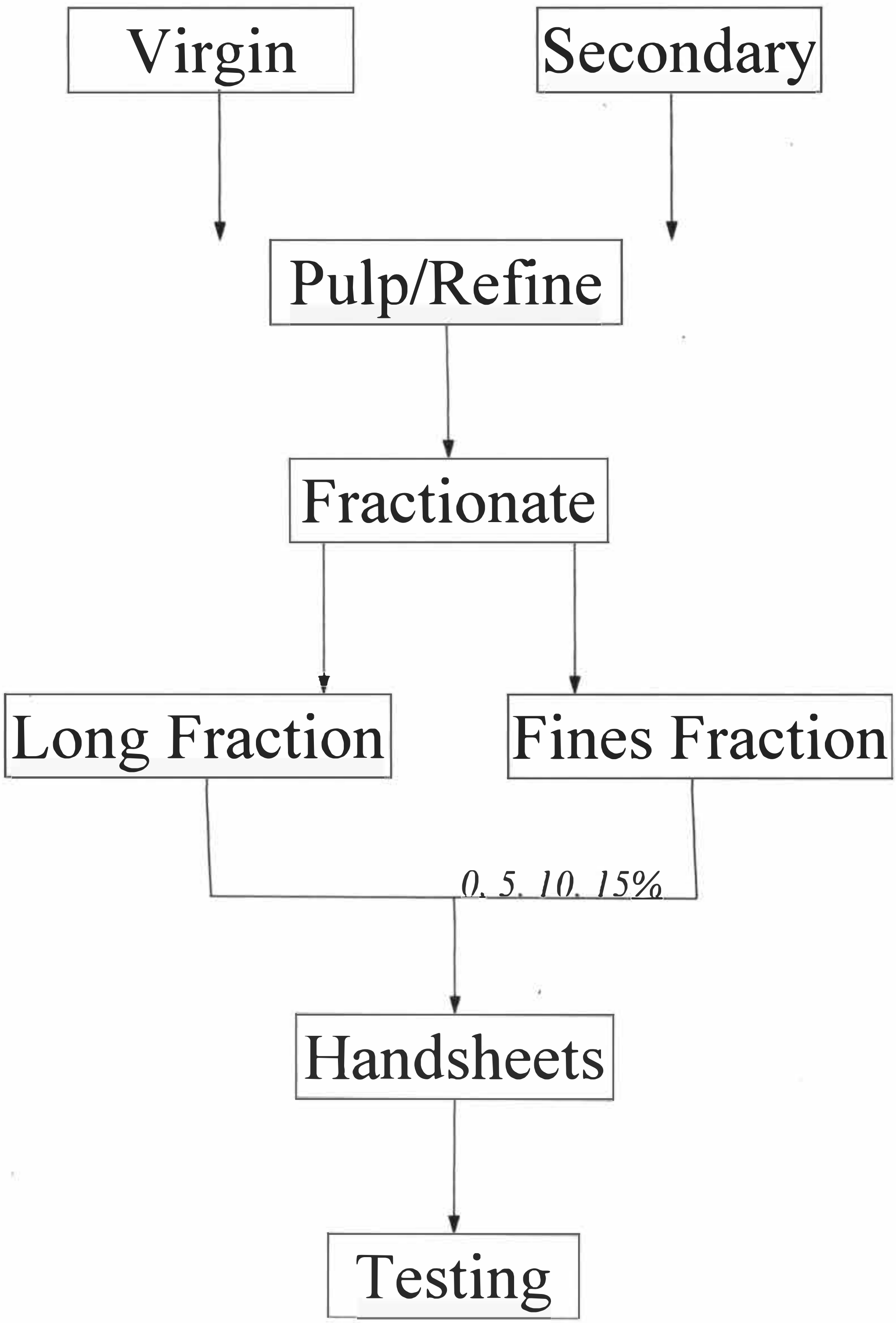
This resulted in 14 different trials as illustrated in the following table:

Table 1: Summary of Trials

	Percentage of fines added by weight			
Virgin long virgin fines	0%	5%	10%	15%
Virgin long secondary fines	same as above	5%	10%	15%
Secondary long virgin fines	0%	5%	10%	15%
Secondary long secondary fines	same as above	5%	10%	15%

The following diagram summarizes the overall procedure:

Figure 3: Procedure Overview



Testing

As for testing, to determine:

Surface strength, the sheets were tested for:

-Wax pick
-Scott Bond

For **Absorbency**, sheets were tested for:

-Parker Porosity
-Tappi Standard T-432, water absorbency for bibulous sheets
-K & N ink test

Smoothness properties were determined by:

-Parker Print-Surf roughness and compressibility
-Sheffield roughness

And finally, for **optical properties**, sheets were tested for:

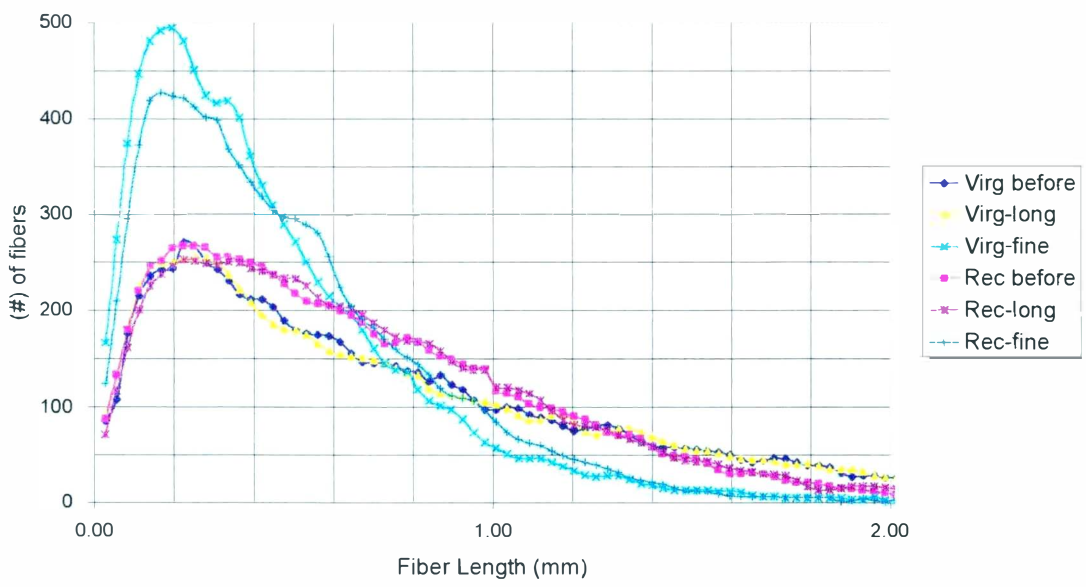
-Opacity
-Scattering Coefficient
-Brightness

Finally, for argumentative support, sheets were tested for density and maximum tensile strength.

PRESENTATION OF RESULTS

In an attempt to determine the efficiency of the fractionation of each stock, the following graph was made using data obtained from the *Fibre Scan* fiber length analyzer:

Figure 4: Float Wash Run Evaluation



As one can easily see, all curves seemed to peak out at about 200 microns. Since there should be thousands of fibers below 200 microns, this test was deemed too insensitive at short lengths. One would expect the two fines curves to continue climbing below 200 microns. This test does however, indicate that only a small fraction of longer fibers was allowed to pass through the screen of the Float Wash Unit.

The following tables include all averaged data from sheet testing:

Miscellaneous

Caliper (mm)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	0.0985	±0.0025	0.0955	±0.0015	0.0962	±0.0027	0.0922	±0.0017
Virg w/rec	0.0985	±0.0025	0.0957	±0.0048	0.0952	±0.0022	0.0967	±0.0017
Rec w/virg	0.1173	±0.0012	0.1115	±0.0081	0.1094	±0.0023	0.1054	±0.0057
Rec w/rec	0.1173	±0.0041	0.1154	±0.0077	0.1119	±0.0065	0.1118	±0.0029

Basis Weight (g/m^2)

fines *added*	0%	5%	10%	15%
Virg w/virg	65.777	64.035	65.598	65.961
Virg w/rec	65.777	63.850	64.171	65.474
Rec w/virg	63.684	63.252	65.696	64.798
Rec w/rec	63.684	64.276	62.829	63.705

Density (g/cm^3)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	0.6678	±0.0085	0.6705	±0.0053	0.6819	±0.0096	0.7154	±0.0066
Virg w/rec	0.6678	±0.0085	0.6672	±0.0167	0.6741	±0.0078	0.6771	±0.0060
Rec w/virg	0.5429	±0.0028	0.5673	±0.0206	0.6005	±0.0063	0.6148	±0.0166
Rec w/rec	0.5429	±0.0095	0.5570	±0.0186	0.5615	±0.0163	0.5698	±0.0074

Tensile (max load) (kg)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	6.35	±0.38	6.75	±0.34	±7.12	0.10	7.09	±0.21
Virg w/rec	6.35	±0.38	6.30	±0.22	±6.37	0.21	6.31	±0.33
Rec w/virg	3.24	±0.13	3.75	±0.14	±4.44	0.15	4.45	±0.24
Rec w/rec	3.24	±0.13	3.21	±0.07	±3.32	0.10	3.36	±0.13

Surface Strength

Scott Internal Bond (10^{-3} ft-lb$_f$)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	175	±13	194	±8	221	±8	289	±22
Virg w/rec	175	±13	178	±10	176	±7	177	±6
Rec w/virg	65	±6	87	±12	109	±8	145	±6
Rec w/rec	65	±6	72	±4	70	±9	87	±7

Wax Pick (# of stick to pass)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	12.8	±0.4	13.4	±0.5	14.2	±0.4	15.8	±0.4
Virg w/rec	12.8	±0.4	12.4	±0.5	12.2	±0.4	12.4	±0.5
Rec w/virg	4.3	±0.5	5.4	±0.5	6.8	±0.4	8.6	±0.5
Rec w/rec	4.3	±0.5	4.2	±0.8	4.6	±0.5	4.6	±0.5

Absorbency

Parker Porosity (mL/min)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	155.4	±18.5	101.4	±5.2	51.49	±4.3	28.81	±2.4
Virg w/rec	155.4	±18.5	160.4	±18.3	141.3	±18.0	122.1	±4.2
Rec w/virg	3072	±174	1232	±65	437.9	±35.0	186.8	±12.4
Rec w/rec	3072	±174	2250	±137	1872	±62	1507	±57

T-432 Water Absorbency Test (seconds)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	58	±12	79	±16	128	±22	133	±26
Virg w/rec	58	±12	75	±14	91	±11	103	±11
Rec w/virg	8.4	±1	20	±4	32	±3	65	±11
Rec w/rec	8.4	±1	11	±2	13	±2	16	±2

(seconds to absorb a 0.052g drop of water)

K&N Ink Test (% - Brightness loss)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	48.17%	±0.63%	44.08%	±0.32%	41.21%	±1.80%	37.24%	±1.92%
Virg w/rec	48.17%	±0.63%	50.02%	±1.23%	49.67%	±0.80%	46.36%	±0.30%
Rec w/virg	58.34%	±0.85%	57.26%	±0.49%	54.61%	±0.82%	50.68%	±1.89%
Rec w/rec	58.34%	±0.85%	57.93%	±0.59%	57.16%	±0.37%	56.75%	±0.58%

Smoothness

Parker Roughness (μM) at 10 kg/cm^2

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	7.8	±0.11	7.7	±0.08	7.7	±0.08	7.8	±0.10
Virg w/rec	7.8	±0.11	7.5	±0.07	7.5	±0.11	7.6	±0.05
Rec w/virg	7.5	±0.04	7.6	±0.11	7.7	±0.08	7.8	±0.09
Rec w/rec	7.5	±0.04	7.6	±0.05	7.6	±0.05	7.6	±0.00

Parker Roughness (μM) at 20 kg/cm^2

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	6.6	±0.13	6.5	±0.05	6.5	±0.10	6.6	±0.11
Virg w/rec	6.6	±0.13	6.4	±0.08	6.4	±0.08	6.4	±0.08
Rec w/virg	6.3	±0.04	6.3	±0.05	6.5	±0.08	6.6	±0.10
Rec w/rec	6.3	±0.04	6.3	±0.05	6.3	±0.07	6.4	±0.06

Parker Compressability

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	1.18	±0.04	1.19	±0.02	1.18	±0.03	1.18	±0.03
Virg w/rec	1.18	±0.04	1.18	±0.03	1.18	±0.03	1.18	±0.02
Rec w/virg	1.18	±0.02	1.20	±0.03	1.19	±0.03	1.19	±0.03
Rec w/rec	1.18	±0.02	1.19	±0.02	1.20	±0.02	1.20	±0.01

(roughness@10kg/cm^2 / roughness@20kg/cm^2)

Sheffield Roughness (units)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	301	±7	299	±4	301	±5	301	±4
Virg w/rec	301	±7	297	±6	287	±4	292	±8
Rec w/virg	302	±8	297	±6	299	±5	304	±4
Rec w/rec	302	±8	296	±6	297	±6	297	±3

Optical Properties

Opacity (Tappi) (%)

fines *added*	0%	5%	10%	15%
Virg w/virg	76.60	75.52	75.87	75.88
Virg w/rec	76.60	76.79	78.35	80.00
Rec w/virg	83.42	83.50	84.58	83.97
Rec w/rec	83.42	84.03	84.28	85.29

Scattering Coefficient

fines *added*	0%	5%	10%	15%
Virg w/virg	33.95	33.28	32.90	32.63
Virg w/rec	33.95	35.13	37.23	39.03
Rec w/virg	46.05	46.56	47.44	46.61
Rec w/rec	46.05	47.00	48.59	50.06

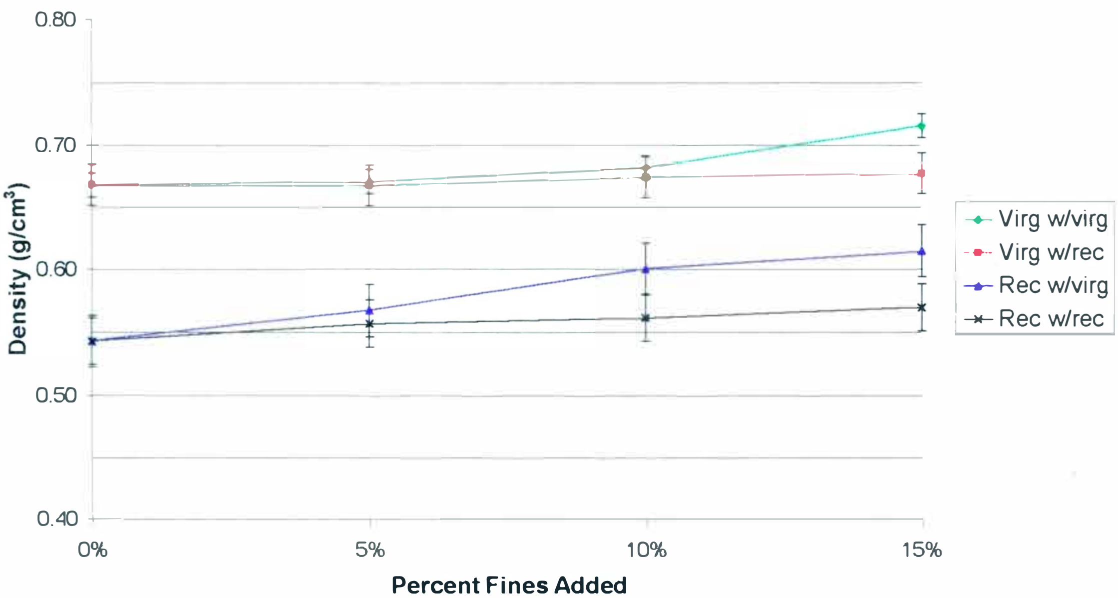
Brightness (%)

fines *added*	0%	std dev	5%	std dev	10%	std dev	15%	std dev
Virg w/virg	88.17	±0.26	87.63	±0.27	86.71	±0.24	85.78	±0.19
Virg w/rec	88.17	±0.26	87.19	±0.25	86.16	±0.33	84.98	±0.22
Rec w/virg	85.40	±0.36	85.27	±0.35	85.24	±0.22	84.62	±0.20
Rec w/rec	85.40	±0.36	84.91	±0.26	84.61	±0.32	83.87	±0.30

The following figures illustrate the effects that fines have on the various properties of interest. *Please note that the lines connecting the data points are only in place as a visual aid, and are not meant to suggest any trends:*

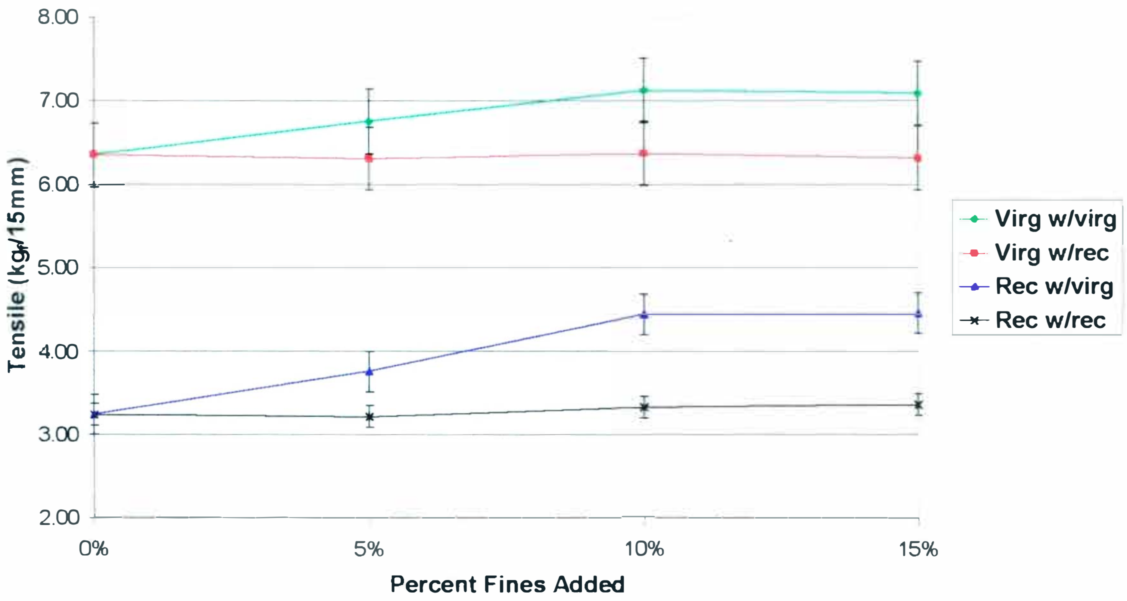
Miscellaneous Properties:

Figure 5: The Effect of Fines on Density



As seen in figure 5, the virgin stocks showed about 40% higher density than the recycled stocks. There was about a 10% increase in density with the highest loading of virgin fines for both base stocks, while there was only a slight increase in density with recycled fines.

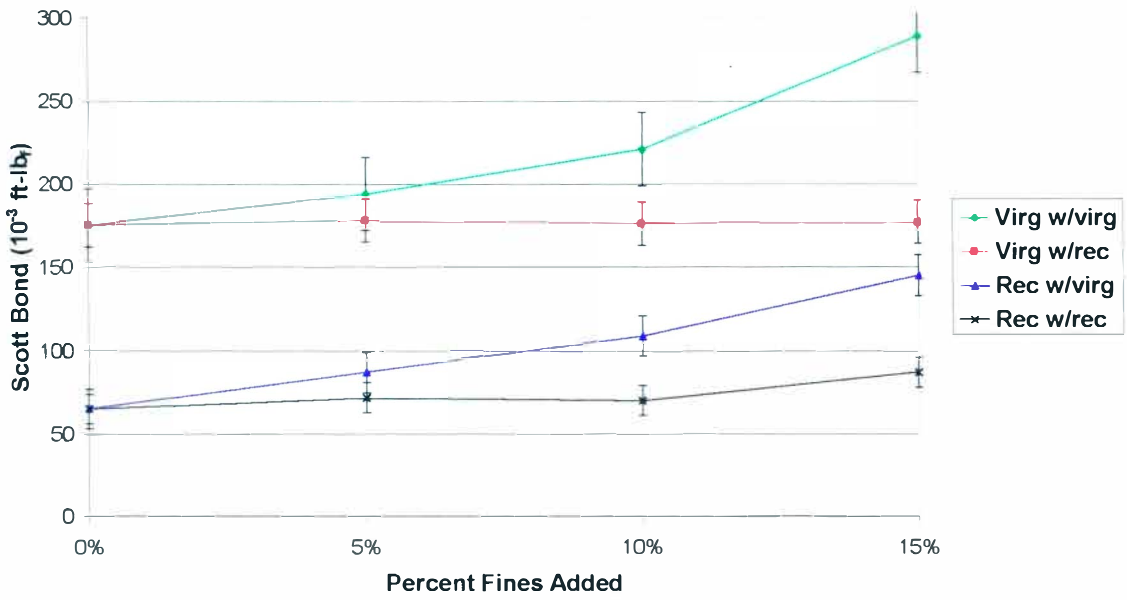
Figure 6: The Effect of Fines on Tensile



The recycled base sheets were about half as strong as the virgin sheets. There was a 30% increase in tensile with the addition of virgin fines, but this leveled off after the 10% addition level, apparently near the point of diminishing returns. The virgin paper's strength peaked out at 7.1, and the recycled peaked out at 4.5. There appeared to be no significant change in tensile with increasing recycled fines.

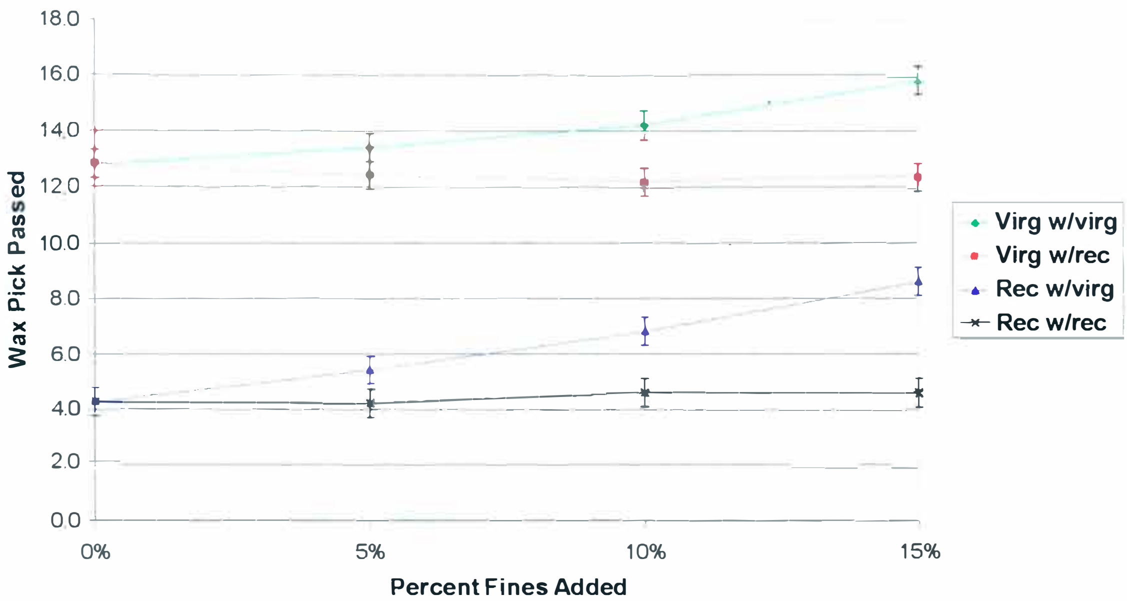
Surface Strength:

Figure 7: The Effect of Fines on Scott Internal Bond



Scott bond is really a test of z-directional tensile strength, but for the purposes of this experiment, it should nicely indicate surface strength as well. As with tensile, Scott bond tests for the virgin sheets showed about twice the strength of the recycled sheets. The addition of recycled fines on virgin sheets appeared to have no effect, while there was about a 30% increase in Scott bond with recycled fines addition to the recycled stock. This was only seen between 10% and 15% fines loading.

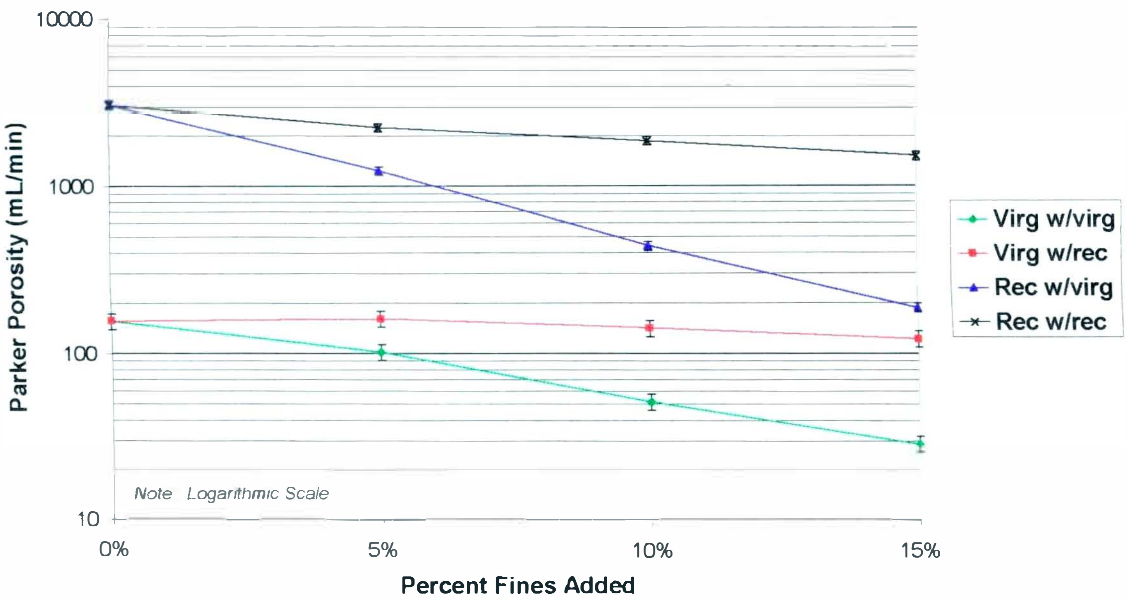
Figure 8: The Effect of Fines on Surface Strength



Wax pick showed results similar to those of Scott bond. The recycled sheets showed about one third the wax pick values of the virgin stocks. There was about a 20% increase in strength with the maximum addition of virgin fines on virgin fiber, while virgin fines nearly doubled the strength of the recycled sheets. The lines for these observations appear to be rather linear, so one might expect this trend to continue to rise beyond 15%, probably leveling off and dropping after a point. Recycled fines, on the other hand, showed no significant effect on surface strength.

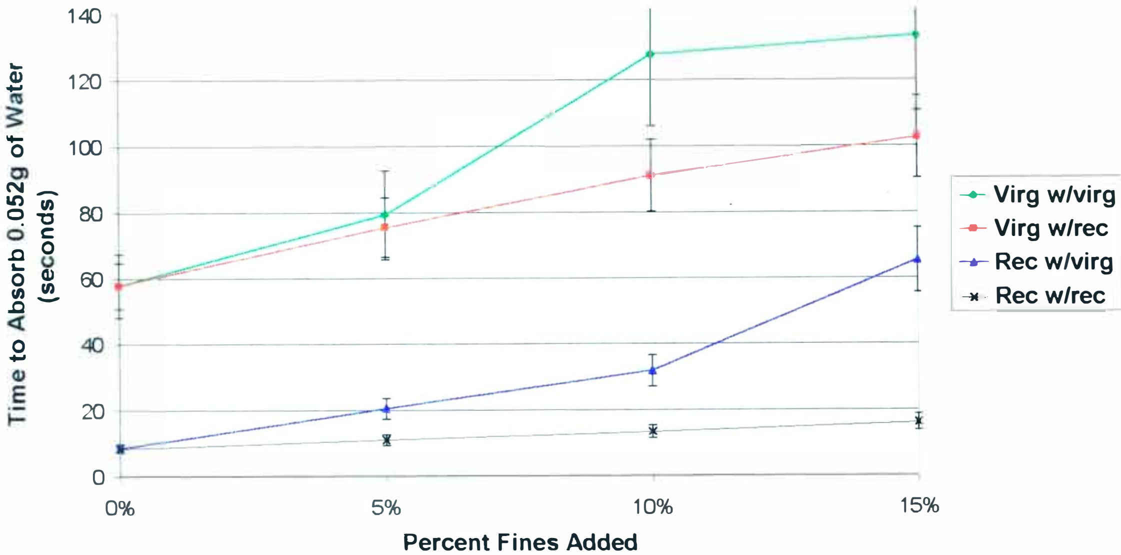
Absorbency:

Figure 9: The Effect of Fines on Parker Porosity



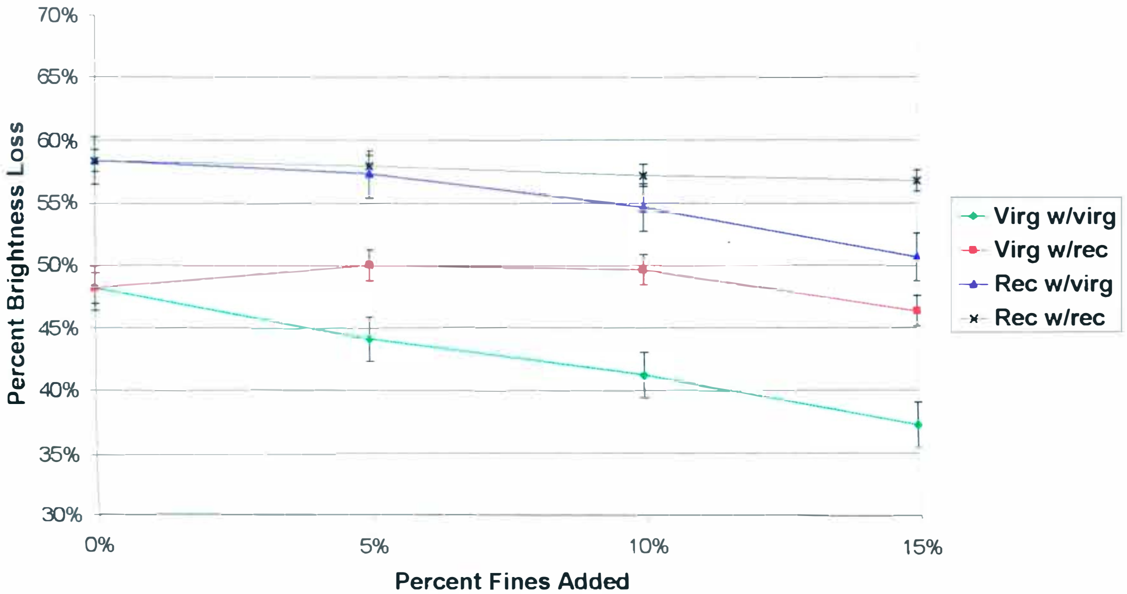
The recycled sheets appeared to be much more porous than the virgin sheets. The addition of virgin fines appeared to have a dramatic effect on the reduction of porosity. From 3000 mL/min down to about 200 mL/min for recycled sheets, and from 155 mL/min down to 30 mL/min for the virgin sheets. Recycled fines, however, showed a more slight change; from 3000 mL/min to 1500 mL/min for recycled base stock, and from 155 mL/min to 122 mL/min.

Figure 10: The Effect of Fines on Water Absorbency
Tappi Method T-432



This test measures the time it takes for a drop of water of known mass to be absorbed into a sheet, as indicated by the loss the of apparent spectral gloss of the drop. Therefore, the longer the time, the *less* absorbent. Overall, the recycled stocks were much more absorbent than the virgin stocks. The virgin stocks appeared to hold out the water almost one minute longer than the recycled stocks. The addition of both fines types increased hold out. The recycled fines addition showed a rather linear increase in hold out, by as much as 75%, but the virgin fines addition increased hold out by about one minute for both base stocks.

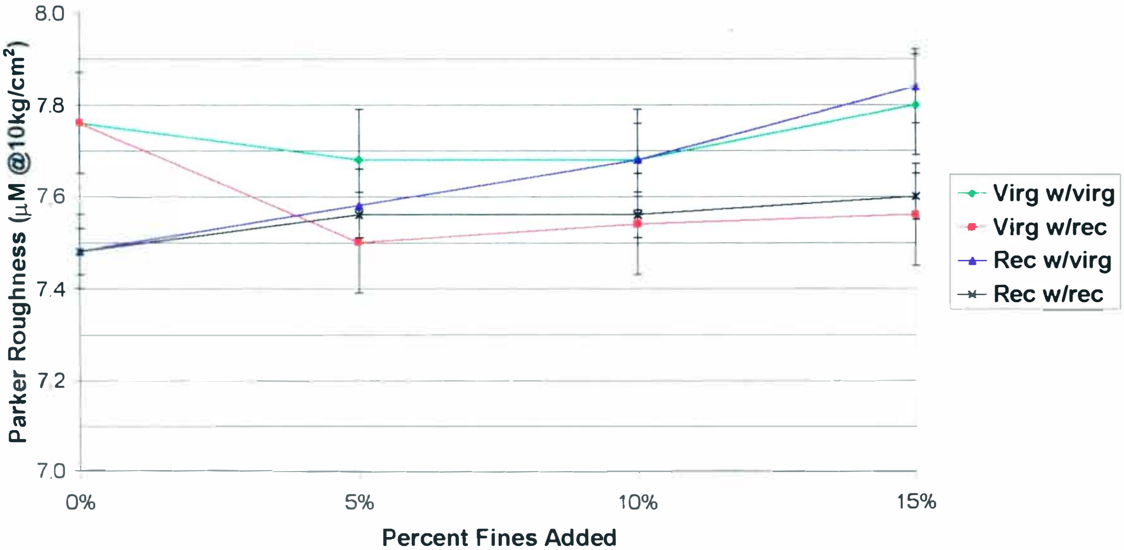
Figure 11: The Effect of Fines on K&N Ink Absorbency



These results are similar to the T-432 results, in that the recycled stock was more absorbent than the virgin stock, and while addition of both fines types decreased penetration, the virgin fines appeared to be more effective at this.

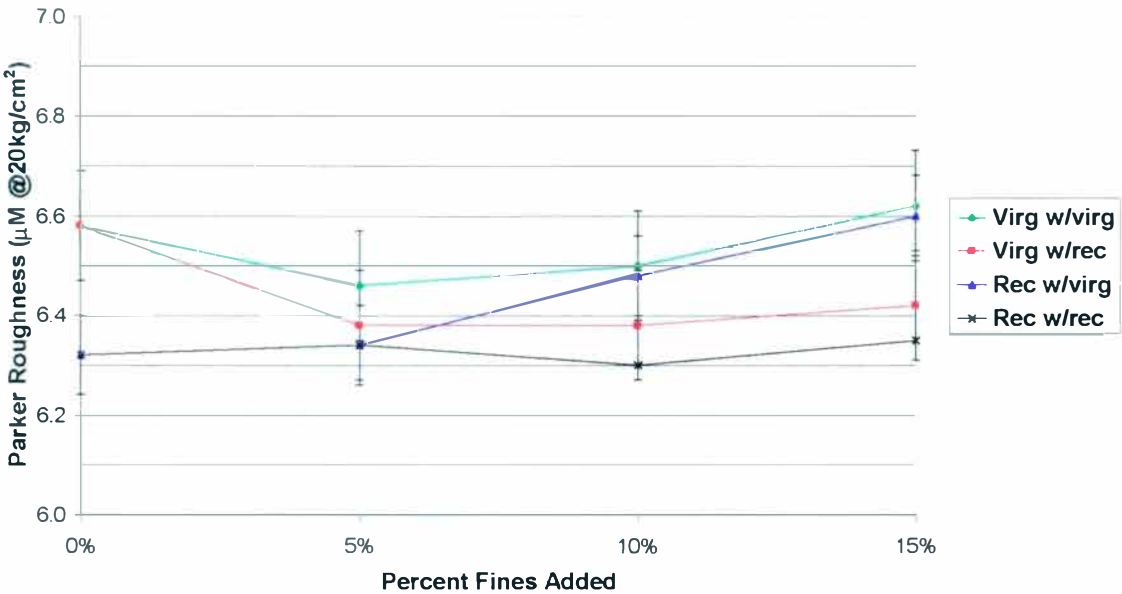
Smoothness:

Figure 12: The Effect of Fines on Parker Roughness
(at 10kg/cm²)



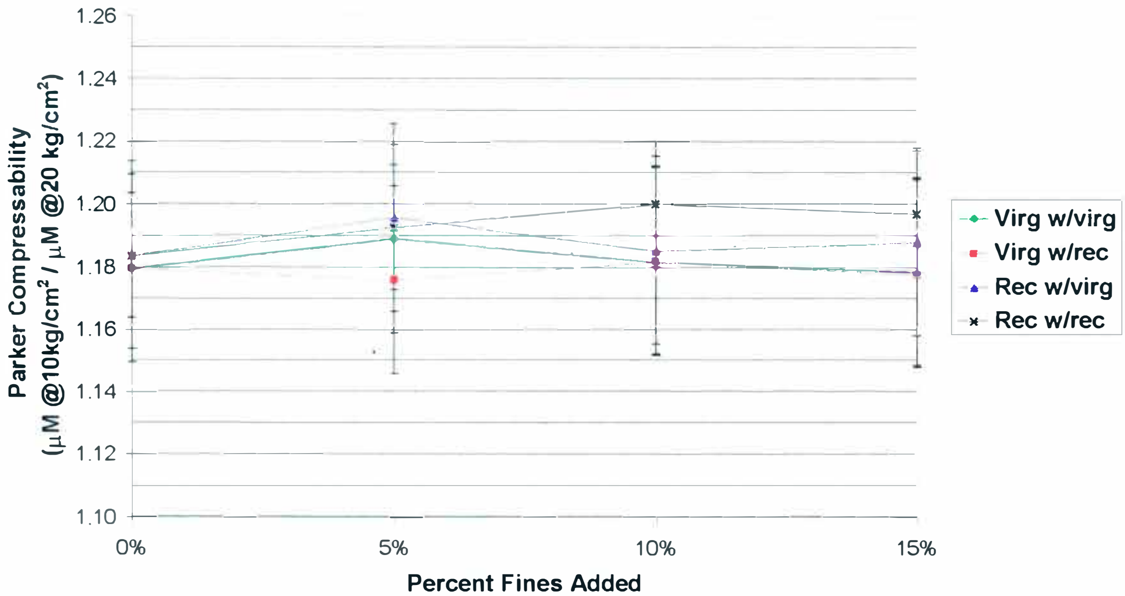
This data appears to show no trend, however one might note that both recycled stocks start out smoother than the virgin stocks, but as fines are added, both stocks with recycled fines end up smoother. The problem here is that the largest difference between observed smoothness readings is about 0.2 microns. This is an incredibly small difference, and it nearly falls within the error bars of the individual points, so little if anything can be concluded from this data.

Figure 13: The Effect of Fines on Parker Roughness
(at 20kg/cm²)



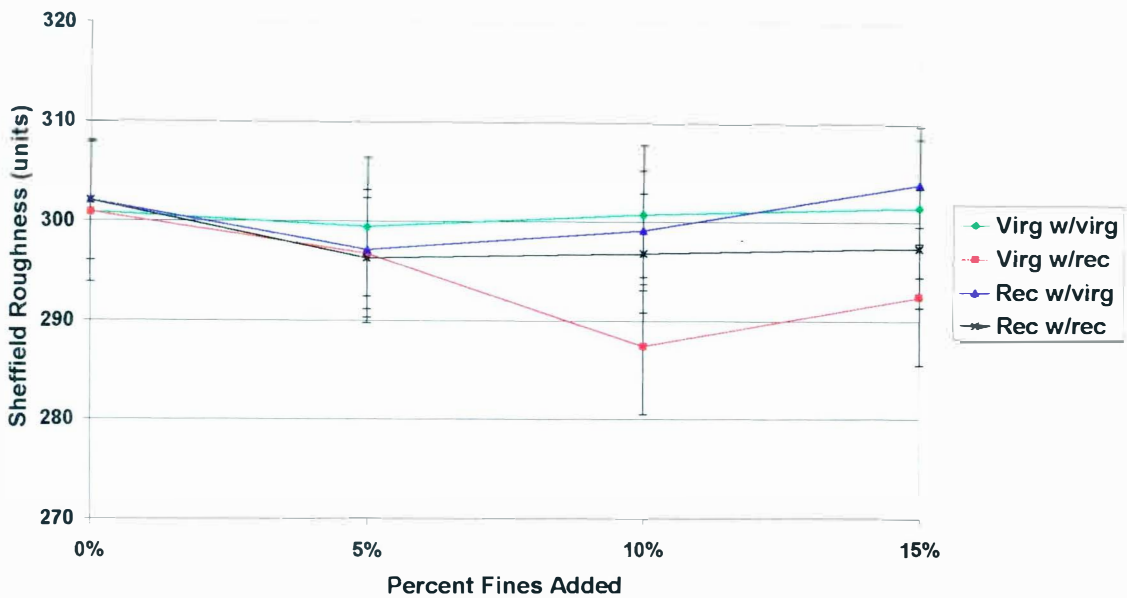
This is simply Parker Roughness measured at a higher pressure ($20 kg/cm^2$). Once again, noticing the scale on the y-axis, there appears to be only very slight differences between each series.

Figure 14: The Effect of Fines on Parker Compressability



Parker compressibility is simply the Parker roughness at 10kg/cm^2 divided by the Parker roughness at 20kg/cm^2. For this reason, this data also appears to be inconclusive, as the error bars' span far exceeds the range of values obtained for compressibility. The only conclusion that could possibly be drawn is that the recycled sheets appear to be slightly more compressible than the virgin sheets. However, this is only about a 1% difference, so it would be difficult to write this observation off as much more than shear coincidence.

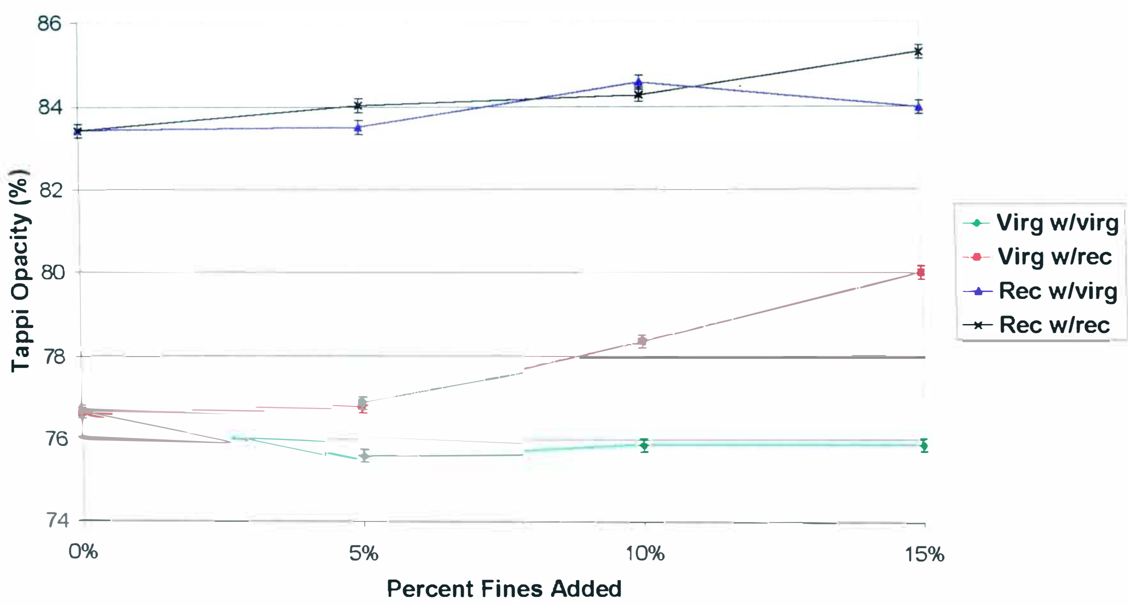
Figure 15: The Effect of Fines on Sheffield Roughness



All sheets started at nearly the same Sheffield roughness value of about 302 units. Then they all gradually separate, and about a 3% greater smoothness is observed for the addition of recycled fines. This supports the observations for both Parker roughness tests, that the recycled fines addition very slightly may have increased smoothness. Another observation to be made when looking at all roughness tests as a whole, is that most series' tend to drop slightly for 5% and 10%, but then rise back up at 15%. This was especially seen with the virgin based sheets.

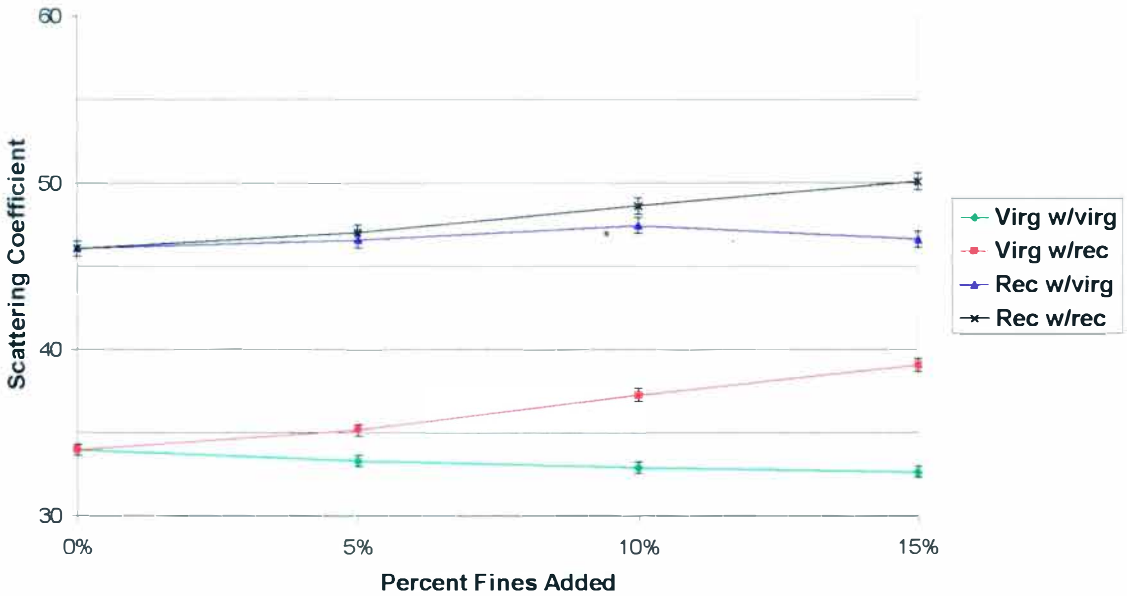
Optical Properties:

Figure 16: The Effect of Fines on Opacity



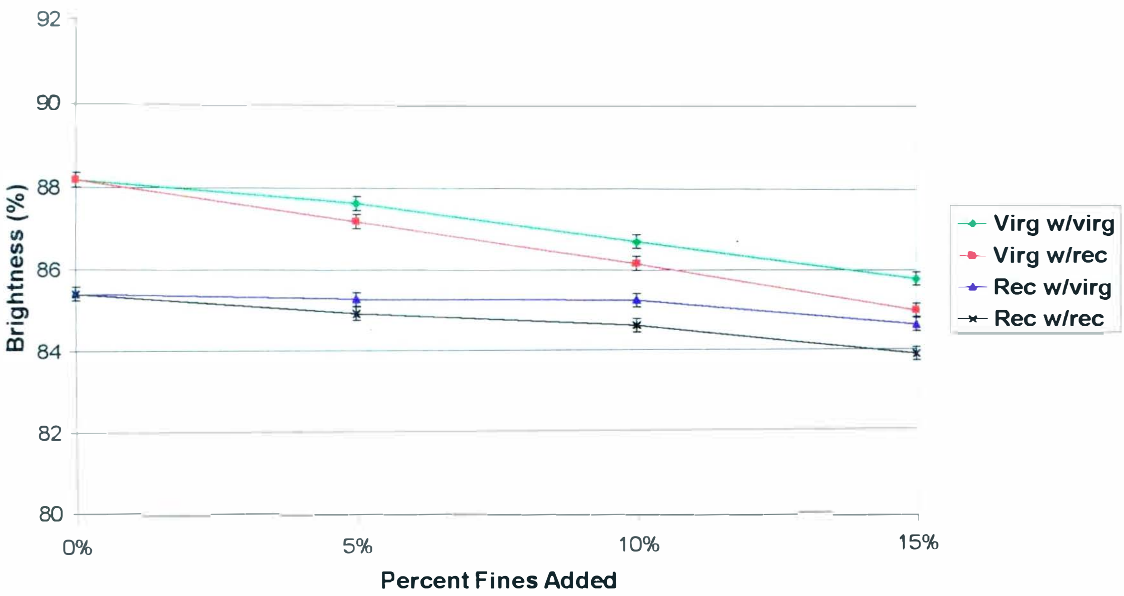
The recycled sheets were about seven percentage points higher in brightness than the virgin sheets. The addition of recycled fines raised opacity by two to three percentage points. The recycled fines appeared to have a greater effect on the virgin based sheets. However, the addition of virgin fines showed mixed results. As they were added to recycled sheets, the opacity rose slightly by about one percentage point. As they were added to virgin sheets, the opacity appeared to decrease by almost one percentage point.

Figure 17: The Effect of Fines on Scattering Coefficient



Scattering coefficient is similar to opacity, but it takes into account the basis weight of the sample. This might explain the better separation of the different fines' type addition. Also, each series here appears to be more linear than for opacity. There was 35% higher scattering with the recycled sheets. The addition of recycled fines appears to have an equal effect on scattering for both base sheet types, causing a 10% increase at maximum loading. Scattering appears to be nearly constant with the addition of virgin fines to recycled sheets, but it dropped slightly with addition to virgin sheets.

Figure 18: The Effect of Fines on Brightness



The brightness for the recycled sheets started out about three percentage points lower than the brightness of the virgin sheets. The addition of fines lowered brightness fairly linearly. As the slopes indicate, the brightness of the virgin stock appeared to be more affected by the addition of fines. Also, the addition of recycled fines showed consistently lower brightness (by about 0.75 percentage points) than the sheets with virgin fines.

DISCUSSION OF RESULTS

Miscellaneous Tests

Miscellaneous tests include density and tensile, which were performed to aid in arguments for the following main categories:

Surface Strength

The weaker surface strength observed for the recycled base sheets is to be expected, as the fibers are hornified, and probably were much less flexible during forming than the virgin fibers. Virgin fibers are much more flexible, they tend to swell more upon wetting, and they will lay down to be more ribbon like during pressing and drying. Recycled fibers, on the other hand, retain their rounded shape and are much less compliable upon forming. This all leads to a greater relative bonded area in the virgin sheets. At fiber-to-fiber intersections, the virgin fibers will overlap more, allowing for greater bonding sites. Also, the quality and number of the microfibrils on the surface of the recycled fibers is probably much less than that of the virgin fibers.

There is also a good possibility that the recycled fibers themselves are weaker than the virgin fibers. They have received much more abuse, likely having gone through twice as many refiner runs as the virgin fibers.

Strength is also dependent upon fiber length. Recycled pulps usually contain shorter fibers because they are less flexible, and during refining they tend to be cut more and fibrillated less than their virgin counterparts.

These theories are supported by the observations for tensile and density. Tensile is a good indicator of the extent of bonding. Here too, the strength of the recycled sheets was about half of the strength of the virgin sheets. The increased density agrees with the theory that virgin fibers are more flexible and will flatten out to be more ribbon-like (i.e. flexible, cooked noodles will pack more densely than will straight, hard noodles) . The virgin fiber web is able to be consolidated more than the recycled web. Also, the greater bonding *potential* (not to be confused with relative bonded area) of the virgin fibers allows the web to remain more tightly consolidated under the pressures of pressing and drying.

The addition of virgin fines dramatically helped the surface strength. When added to the recycled base stock, the 15% loading level nearly took the Scott bond strength as high as the virgin stock with 0% loading. This effect is seen because the virgin fines are very active, meaning they probably have a lot of surface area available for bonding. Their size allows them to get in between fibers and along fiber-to-fiber intersections to supplement fiber bonding. The term “glue effect” has been used to describe this phenomenon.

Recycled fines appeared to have little effect on surface strength. This result could probably go either way in a different experiment using a different recycled stock. If the broke that was used had received more gentle treatment when it was made, then perhaps the fines would be more active and would improve strength. However, if the treatment was more rough, then it would be easy to assume that the fines addition would hurt strength, but another experiment would need to be run in order to verify this. Fines activity may be a function of the number of recycles as opposed the level of treatment. It could be that they are totally inert, and that their small size prevents them from inhibiting bonding at small concentrations.

Surface strength is very important to printing, especially where high tack inks are used, as in offset lithography. A low surface strength will ultimately result in excess linting and picking of fiber bundles from the surface of the sheet, and dusting of the edges where trimming and cutting occur. If these contaminants get caught on the press blanket, then the image will not transfer where the particle lies.

The main conclusions to be drawn here are that recycled papers have a much greater risk of linting, picking, and dusting than do virgin papers; and that while virgin fines addition would reduce picking, a change in the level of recycled fines would show minimal change in surface failure rate (at these concentrations).

Absorbency

Porosity is sometimes used as an indicator of how a substrate will absorb a solvent. As figures 9-11 show, this practice appears to be valid for this experiment as well. Parker porosity measures the air permeability of a sheet. It is the number of milliliters of air that can pass through a certain area of a sheet at a given pressure. The logarithmic scale was chosen because by nature, when something affects porosity, it usually does so exponentially. The linear plots in figure 9 illustrate this nicely.

The increase in porosity with recycled paper exists for the same reason that the decrease in density exists: with recycling, the fibers will not lay down as well, as they are much less flexible. Since much of the absorption of liquids into a sheet depends on the micro-capillary action on surface of the sheet, one should see a great increase in absorption with recycled paper. Both figures 10 and 11 prove this very well.

With increasing virgin fines, absorption of liquids dropped rapidly. This is also due to the densification or consolidation of the fiber web. Recycled fines decreased absorption slightly, possibly due to void filling or even because of a slight aid in bonding. Because density did not change with increasing recycled fines, one would not expect the porosity or absorbtivity to change. It could be that the density calculations are not sensitive enough to detect very slight changes in sheet packing.

Overall, recycling caused the sheet to become much more absorbent, so when printing, solvent trapping and/or show through could become a problem. However, with increasing interest in the use water based inks, recycled papers could be a possibility for this application. This is because they would absorb the water quickly, but would be less apt to curl and cockle because of the fibers' inability to swell as much upon wetting.

When printing, an increase in fines content will cause less penetration and show through, and greater ink hold out. This could be a bonus for lighter weight sheets, as the opacity of the sheet will be less, and ink show through becomes more of an issue. Recycled fines would simply show a much less profound effect on hold out.

Smoothness

Although one might expect increasing fines to increase the smoothness of a sheet, this was not the case. Also, no conclusions could be drawn to differentiate recycled from virgin stock. As shown in figures 12, 13, & 15, there is a slight possibility that the addition of recycled fines increased smoothness, but the amounts were so small that no real conclusions could be drawn. If these observations do have basis, then they could be the result of void filling. One would expect the recycled sheets to be more compressible because they start out with a higher bulk, but as shown in figure 14, no positive conclusions can be made.

The lack of positive results could be the result of the handsheet's surface conforming to the surface of the blotter paper. This would explain why all smoothness values were nearly the same. This would buffer subtle differences between trials.

Higher smoothness generally means better print reproduction, especially with roto-gravure printing, where the sheet must be smooth enough to make good contact with the ink in each cell in order to pull the ink out of the cells. According to this data, increased recycled fines should have little to no effect on printing (*by virtue of smoothness*).

Optical Properties

The recycled sheets gave about seven percentage points higher opacity (figure 16) and 35% higher light scattering (figure 17) because of weaker bonding and therefore lower density of the recycled sheets. The lower the density, the greater the number of void spaces and fiber-to-air interfaces. Since fibers and air have different refractive indices, light will bend when it hits these interfaces. The net effect of thousands of these interfaces gives the paper its light scattering ability. To cause a sheet to be opaque, the fiber mat must either be thick enough to absorb the light, or have the ability to scatter the light. Therefore, for a given basis weight, especially with lighter sheets, differences in opacity are the result of differences in scattering ability.

The increase of opacity and light scattering with increased recycled fines is seen because the recycled fines are not as firmly bonded to the sheet, causing more of these refractive interfaces to exist. Although it is expected that increasing virgin fines would decrease opacity, the data shows mixed results. The main conclusion here is that virgin fines addition to the recycled stock raised opacity, and their addition to virgin sheets lowered opacity. This is possibly seen because while the virgin fines have a great potential for bonding, the recycled fibers do not, therefore the virgin fines have a limited ability to attach to the recycled fibers. The evidence shown by tensile and surface strength, however, show that the virgin fines really are adding to the bonding within a recycled sheet. It should be noted though, that the increase in opacity and scattering with the virgin fines was only very slight.

As for brightness, as expected, the recycled stock produced sheets with lower brightness than the virgin stock (figure 18). This is because the recycled stock has already been through a paper making process at least once, so the paper is inherently impure.

The addition of both fines types lowered brightness. This probably happened because during fractionation, fines are not the only things that pass through the screen. Every other small piece of dirt or contamination in the stock is allowed to pass through with the fines fraction, therefore the opportunity exists for higher concentrations of contaminants in the fines fraction. The addition of recycled fines showed a slightly larger effect on brightness loss because the recycled fines fraction has a greater opportunity for contamination than the virgin fines fraction. It might be best to consider that the reduction of brightness with fines is the result of the fractionation process, and not the result of any property of the fines themselves.

As for printing effects, the more opaque a sheet, the smaller the chance for ink show through and light penetration, especially with lighter weight sheets. Recycled paper, therefore, will experience less show through (for equal absorption) than comparable virgin paper. An increase in recycled fines content will also reduce show through. This is especially important with sheets that are printed on both sides. Brightness is important to printing because the brighter the sheet, the greater the contrast between the substrate and the printed image. Even though the recycled stock came out with lower brightness, the difference was only by about 2.5 percentage points, definitely not significant enough to warrant the use of virgin over recycled stock. Increasing fines content would probably hurt print contrast only as the result of fractionation, and not as the result of their mere presence.

CONCLUSIONS

Because of weaker surface strength, recycled papers will have a greater tendency for linting, picking, and dusting in the printing press. While increasing fines in a virgin sheet reduces picking, a change in the level of fines (at least at the concentrations used in this experiment) in a recycled sheet would show minimal change in surface failure rate. Basically, the recycled fines were much less active and appeared to play little if any role in the bonding within a sheet.

While recycled paper appeared to be much more absorbent than virgin paper, the addition of both fines types would increase the ink hold out ability of the sheet. This results in reduced solvent penetration and show through. Again, recycled fines played a smaller role in this effect compared to virgin fines.

Higher smoothness results in better print quality, but from this experiment, no concrete conclusions could be drawn for either the effects of recycling, or the effects of fines. One might expect increasing fines to increase smoothness, but this data did not show this.

Both recycling and increased recycled fines content showed greater opacity and reduced brightness. The increased opacity along with the reduced absorptivity with increasing recycled fines both indicate that recycled papers with increased fines content will show significantly lower ink show through.

Overall, with the exception of opacity, fines appear to play a much smaller role in paper making when the paper is recycled. The fines were more inert and tended to be more along for the ride. As predicted, they appeared to be much less active than when they were in virgin form.

RECOMMENDATIONS

Adding virgin fines to a recycled stock would be useful in regaining much of the lost strength seen with recycled paper, without significantly hurting opacity. On the other hand, recycled fines could be added to a virgin stock to increase opacity without significantly hurting strength properties. These methods would be useful only if the fractionation process could be made efficient and economical on a mill scale.

For future work, one could do a cost analysis and try to estimate if the above theories could be effectively put into practice. Also, one could run an experiment to determine the effects of fines refined to varied intensities. Finally, one could determine the effects of the number of recycles on the quality of the fines, focusing mostly on strength properties.

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