

Impact of pulp chemical composition on recycling

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PAPER RECYCLING CAUSES MAJOR changes in the strength and optical properties of pulps. In general, recycling tends to decrease tensile strength, burst strength, and folding endurance while increasing tear resistance, stiffness, light scattering, and opacity. However, the magnitude of change upon recycling is different for different types of pulps (kraft, sulfite, mechanical, etc.). Pulp recycling potential—the ability to retain physical properties after recycling—depends on its pulping and papermaking history. Chemical pulps exhibit pronounced changes, while mechanical pulps remain relatively insensitive to recycling.

BACKGROUND

Previous researchers have speculated that the different responses for mechanical and chemical pulps arise from the relative amount of lignin present in the fibers (1–3). Scallan and Tigerstrom (4) studied fiber saturation points for a series of pulps with yields ranging from 40% to 100%. The swelling behaviors of never-dried and recycled pulps were then compared as a function of yield. It was shown that, at higher pulp yields, pulp swellability after recycling was almost completely recovered. At lower yields, increasing irreversibility was observed. Therefore, Scallan and Tigerstrom suggested that the strength loss upon recycling was a feature of low-yield pulps. The common explanation for this behavior is that removal of the lignin-hemicellulose gel provides an

opportunity for greater intermolecular mobility and contact with the carbohydrate component (3). On the other hand, if there is enough lignin present, the composite lignin-carbohydrate cell structure is rigid enough to resist collapse from surface tension upon drying.

Despite the acceptance of this explanation by many researchers, there is some inconsistency with regard to the role of lignin on the recycling behavior of pulps. Klunness and Caulfield (5) studied the effects of recycling on three loblolly pine kraft pulps. Two of them were unbleached pulps with 46% and 60% yields. The third was a bleached pulp with 46% yield. Their Klason lignin contents were 16.2%, 4.8%, and 0.2%, respectively. It was found that the percentage loss of strength properties with recycling did not correlate well with the gradual removal of lignin content in the pulps. In another study, Lundberg and de Ruvo (6) compared the strength and drainage characteristics after recycling kraft pulps treated with and without chlorine. The yields of three regular kraft pulps, without any chlorine treatment, were 47%, 55%, and 59%. Another kraft pulp of initial yield 65% was subjected to varying chlorine and alkali treatments to obtain yields of 52%, 58%, and 63%. It was found that in the case of regular kraft pulps, without any chlorine treatment, the strength loss after recycling increased with decreasing yield. However, this trend was less pronounced for the chlorine-treated pulps, which suffered less strength

RECYCLING

ABSTRACT

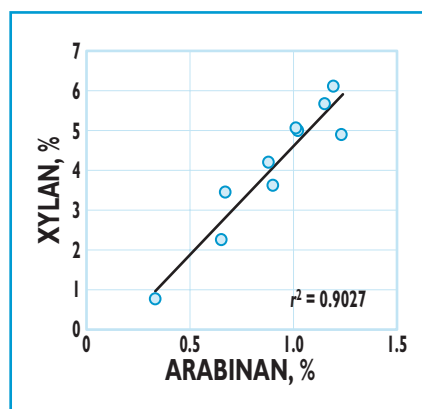
The effects of hemicellulose and lignin on recycled pulp quality were studied using hemlock pulps. The amount of pentosans in the pulps played a critical role in their recycling potential, with pulp recyclability improving with higher pentosan content. This effect was observed in both low-yield chemical pulps and ultrahigh-yield chemimechanical pulps. For five pulp properties (apparent density, tensile strength, burst strength, tear resistance, and light-scattering coefficient), the magnitude of changes induced by recycling can be statistically explained by the variation of pentosan content alone. Lignin content did not significantly affect the recycling potential of these pulps. A mechanism is proposed to explain how xylan molecules could influence pulp recyclability.

Application:

Demonstrates that pulp hemicellulose content—principally pentosans and especially xylan—governs the strength and optical properties of recycled pulps.

loss at a given level of pulp yield. It is known that chlorine treatment is more selective in removing lignin and preserving hemicellulose than the conventional kraft pulping process. Hence, as the yields were decreased via chlorine treatment, lignin was selectively removed, and the hemicellulose content was maintained at a relatively high level. This may have contributed to the difference in recycling response between the two series of pulps, thus suggesting that lignin and hemicellulose contents in pulps may influence the recycling behavior differently.

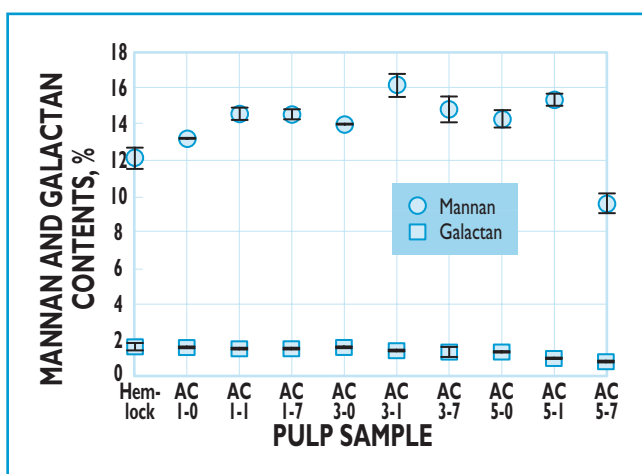
There is some speculation in the literature regarding the role of hemicellulose in the re-formation of paper. Gallay (7) speculated that the loss of wet plasticity was related to



1. Pentosan content (xylan and arabinan) in western hemlock pulp samples

Pulp	Lignin, %	PENTOSANS		HEXOSANS		
		Arabinan, %	Xylan, %	Mannan, %	Galactan %	Glucan %
Group 1: low lignin content and contrasting pentosan content						
A	4.7	0.7	2.3	14.8	1.4	70.6
B	5.5	0.9	4.2	16.1	1.4	62.9
C	4.9	1.2	6.1	14.3	1.4	60.1
Group 2: high lignin content and contrasting pentosan content						
D	17.2	1.0	5.1	14.5	1.5	52.9
E	16.2	0.9	3.6	14.5	1.5	56.2
Group 3: contrasting lignin content and constant pentosan content						
C	4.9	1.2	6.1	14.3	1.4	60.1
F	10.9	1.2	5.7	14.0	1.5	53.2

1. Lignin and carbohydrate content of pulp samples (based on o.d. pulp weight)



2. Hexosan content (mannan and galactan) in western hemlock pulp samples (error bars represent 95% confidence interval)

the formation of ordered regions within the fiber. Hemicellulose may be partly involved in the formation of this new ordered region. Thereby, the hemicellulose would become inaccessible and unable to contribute to the hydrogen bonding in remaking of paper. Eastwood and Clarke (8) expressed a similar opinion. Giertz (9) suggested that "hornification" takes place, for the main part, within the hemicellulosic material of the fibers because of the high degree of swelling and mobility of the molecules.

Beyond these speculations, there has been little effort to understand the role of hemicellulose on recycling. Moreover, in past studies, the effects of lignin and hemicellulose were frequently mixed, since lignin and hemicellulose are removed with relatively low selectivity in the common commercial chemical pulping processes. Therefore, the objectives of this study were to separate the effects of lignin and hemicellulose and evaluate their relative importance in influencing pulp recycling potential in terms of strength property losses.

EXPERIMENTAL

Selective delignification

Never-dried western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) thermomechanical pulp was the starting raw material. Lignin was selectively removed with sodium chlorite. The degree of delignification was controlled by setting the reaction time at 1.0, 3.0, or 5.0 h. A pulp containing 75 g oven-dry (o.d.) solids was weighed and transferred to a 6 L reactor. Deionized water (2400 mL), glacial acetic acid (7.5 mL), and sodium chlorite (22.5 g) were added successively. The reactor was kept in a water bath, and the temperature was adjusted to $75 \pm 3^\circ\text{C}$. The pulp was stirred once every 15 min. After each hour of reaction, another 7.5 mL glacial acetic acid and 22.5 g sodium chlorite were added until the preset reaction time was reached. The whole operation was carried out in a well-ventilated fume hood. At the end of reaction, the pulp was rapidly cooled with 5°C water. The pulp was then washed thoroughly in a 200-thread cotton bag until the filtrate tested neutral.

Alkaline extraction

The delignified pulps were extracted with 1.0% and 7.0% sodium hydroxide at a pulp-to-liquor ratio of 1.5:100. For each batch of extraction, a pulp containing 100 g o.d. solids was weighed and dispersed in a standard disintegrator for 25,000 revolutions. The pulp was transferred to a 10 L container and diluted with deionized water. Sodium hydroxide solution was added to the container while stirring the slurry. The stirring action was gentle enough to prevent drawing air into pulp. After 5 min of extraction at $23 \pm 2^\circ\text{C}$, the slurry was washed thoroughly until the filtrate tested neutral. The washed pulp was diluted and allowed to sit at least 24 hours to allow residual alkali to leach out of fiber. The pulp was washed again until the filtrate tested neutral.

Chemical analysis

The carbohydrate composition of the hemlock pulps was determined following a previously described procedure (10). Klason lignin was determined according to TAPPI T 222 om-88 with a slight modification. (The sample was

steamed at 121°C for 1 h in an autoclave instead of boiling for 4 h under atmospheric conditions.)

Paper recycling

Repetitive recycling was carried out on handsheets made from delignified and alkali-extracted pulps. Never-dried pulps were first dispersed in a British disintegrator for 50,000 revolutions at a consistency of about 1.2%. After forming on a sheet mold, wet sheets were pressed at 50 psi for 5 min on one side and then 2 min on the other. Ten handsheets were placed in a humidity-controlled room according to TAPPI T 402 and tested for physical properties 24 h later. The rest of the handsheets were dried on a stainless steel hot plate at 95°C for 8–10 min and then soaked in deionized water for at least 12 h. The rewetted handsheets were disintegrated for 50,000 revolutions. Most of the recycled pulp was remade into handsheets and dried according to the described procedure. The recycling procedure was repeated for a total of four cycles.

Physical properties testing

Physical properties of handsheets were tested after each recycle in accordance with the appropriate TAPPI test method: tensile strength (T 494 om-88), burst strength (T 403 om-88), tear resistance (T 414 om-88), thickness and apparent density (T 220 om-88), and light-scattering coefficient (T 220 om-88). Water-retention value was determined using Abson's method (11).

RESULTS AND DISCUSSION

Pulps

To obtain pulps with different chemical composition, hemlock TMP obtained from a west coast pulp mill was treated with acidic chlorite and caustic. These treatments were similar to the preparation of holocellulose pulps. However, the delignification time and caustic concentration were varied so that variable amounts of lignin and hemicellulose were retained. While the variable lignin con-

tent was readily achieved, it is a bit more complicated to obtain variable but comparable hemicellulose content because there are two major groups of hemicellulose in hemlock pulps: arabinoxylan and glucomannan. The approach taken in this study was to extract the partially delignified pulps with different caustic concentrations (0, 1%, and 7%). Since glucomannan is fairly resistant to dilute alkali treatment, it is largely retained in the pulp fibers. Arabinoxylan is readily dissolved in the alkaline solution, and the amount dissolved depends on the caustic concentration. Thus, the pulps that were prepared for this study contained different amounts of arabinoxylan but had approximately the same glucomannan content.

The amount of nonglucose monosaccharides is plotted in **Figs. 1 and 2**. Pulps of widely varying pentosan contents were obtained by the chemical treatments, as seen in Fig. 1. The xylan content ranges from 0.8% to 6.1%. The range for the arabinan content is much narrower, but despite the slight variation of arabinan content among the pulps, it shows a good correlation with xylan content. This is because both come from the same group of hemicellulose, i.e., arabinoxylan. Figure 2 shows that the amounts of mannan and galactan remained fairly constant in most of the pulp samples, as expected. Because the hexosan fraction of hemicellulose in the pulp samples was fairly constant, it is possible to study the effects of the pentosan fraction of hemicellulose on the recycling without interference from the hexosan fraction.

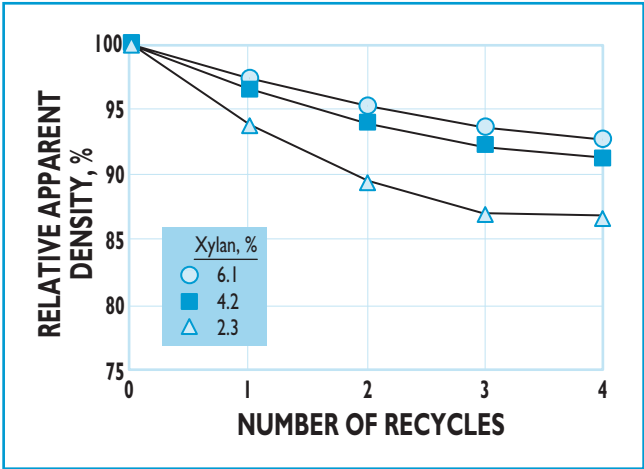
The pulps were sorted into three groups, depending on their chemical composition, to provide a basis for comparative studies. The lignin and carbohydrate compositions of the various pulps are listed in **Table I**. The three pulps in Group 1 have a low lignin content of about 5%, which is equivalent to an un-

bleached chemical pulp. The mannan and galactan contents in these pulps are approximately the same, while the xylan and arabinan contents vary. The two pulps in Group 2 have a high lignin content of about 16.7%, which is equivalent to a high-yield chemimechanical pulp. Again, the mannan and galactan contents are similar, while the xylan and arabinan contents vary. In both cases, the similarity in lignin content and hexosan content within each group makes it possible to study the impact of pentosan content on the pulp recycling behavior. The two pulps in Group 3 contain approximately the same amounts of xylan, arabinan, mannan, and galactan, but their lignin contents are significantly different. This makes it possible to evaluate the effect of lignin on pulp recyclability because it eliminates the effects of hemicellulose, which can otherwise mask the effect of lignin.

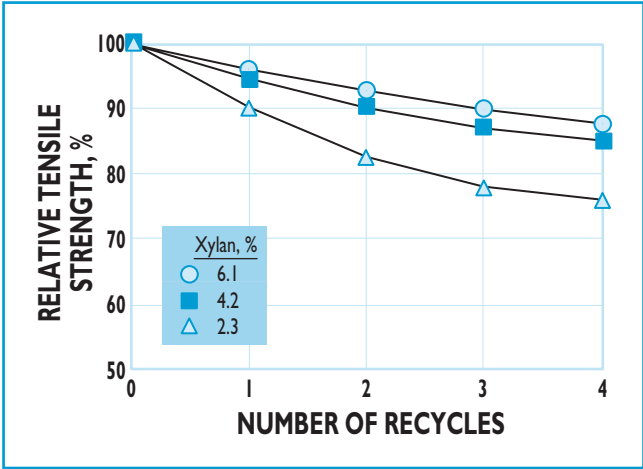
Effects of xylan and lignin on pulp properties

Figures 3–5 show the effects of xylan content on pulp properties (apparent density, tensile strength, and burst strength, respectively) for the low-lignin pulps (Group 1 in Table I) after repetitive recycles. As the amount of xylan in the pulps decreases from 6.1% to 2.3%, pulp strength decreases significantly with the number of recycles. Increasing xylan content mitigated the losses in pulp properties after repetitive recycles. The loss in apparent density compared with virgin pulp shrank from 13% at the lowest xylan content to 7% at the highest xylan content (Fig. 3). Similarly, the loss in tensile strength decreased from 25% to 12% (Fig. 4), and the loss in burst strength dropped from 25% to 10% (Fig. 5).

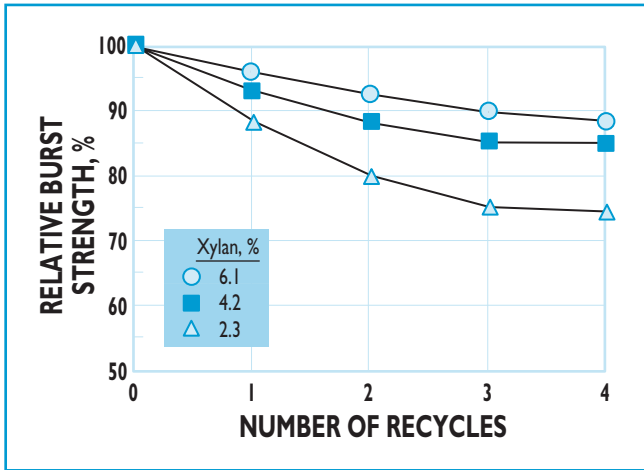
Figures 6–8 show the effects of xylan content on pulp properties (apparent density, tensile strength, and burst strength, respectively) for the high-lignin pulps (Group 2 in Table I) after repetitive recycles. A



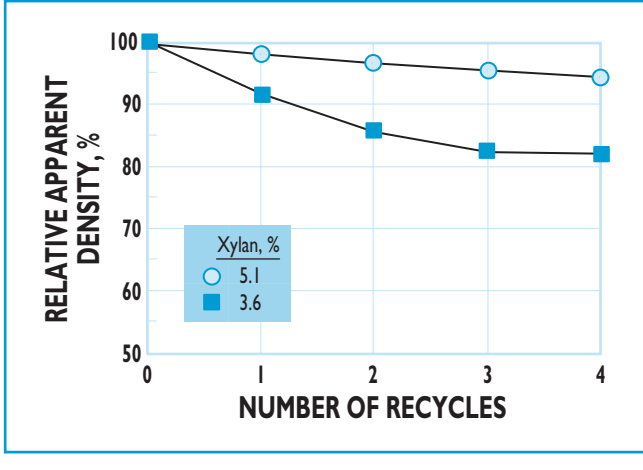
3. Changes in apparent density during recycling of Group 1 pulps (constant, low lignin content $\approx 5\%$; relative apparent density based on virgin pulp)



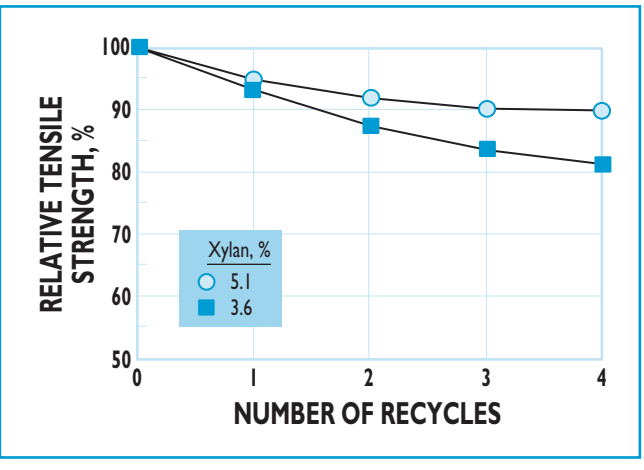
4. Changes in tensile strength during recycling of Group 1 pulps (constant, low lignin content $\approx 5\%$; relative tensile strength based on virgin pulp)



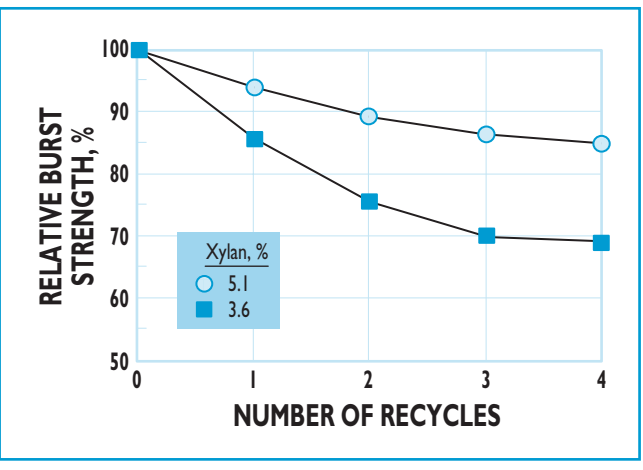
5. Changes in burst strength during recycling of Group 1 pulps (constant, low lignin content $\approx 5\%$; relative burst strength based on virgin pulp)



6. Changes in apparent density during recycling of Group 2 pulps (constant, high lignin content $\approx 17\%$; relative apparent density based on virgin pulp)



7. Changes in tensile strength during recycling of Group 2 pulps (constant, high lignin content $\approx 17\%$; relative tensile strength based on virgin pulp)



8. Changes in burst strength during recycling of Group 2 pulps (constant, high lignin content $\approx 17\%$; relative burst strength based on virgin pulp)

similar trend was observed for the effect of xylan on pulp properties after repetitive recycles. Thus it appears that the effect of xylan on recycling potential is applicable over a wide range of lignin contents.

The effect of lignin on recycling was demonstrated by comparing pulps (Group 3 in Table I) with similar xylan content (5.7% and 6.1%) but varying lignin content (4.9% and 10.9%). **Figures 9–11** illustrate the effects of lignin content on pulp properties (apparent density, tensile strength, and burst strength, respectively) for the pulps of similar xylan content. It is clear from these figures that the two pulps do not appreciably differ from each other in their recycling behavior.

The effect of xylan on recycling was further studied by plotting the total percent change in handsheet properties (apparent density, tensile strength, burst strength, tear resistance, and light-scattering coefficient) after four-time recycling against the amount of xylan present in the pulps, as shown in **Figs. 12–16**, respectively. All five handsheet properties appear to correlate linearly with xylan content. The extent of loss in apparent density, burst strength, and tensile strength diminishes with increasing xylan content in the pulp. Similarly, the extent of increase in light scattering and tear resistance decreases with increasing xylan content in the pulp. For instance, Fig. 12 shows that at 6% xylan content, the pulp loses about 5.8% of its apparent density after four recycles, while at 0.8% xylan content, the pulp loses about 14% of its apparent density. The losses in tensile and burst strength on recycling show a similar trend, as seen in Figs. 13 and 14, respectively. At 0.8% xylan content, the losses in tensile and burst strength are 25% and 29%, respectively, while at 6% xylan content, the losses are only about 11% for both strength indices.

Unlike xylan content, pulp lignin content does not appear to correlate well with the magnitude of change in physical properties after recycling, as seen in **Figs. 17–21**. Of the five selected properties, the largest correlation coefficient obtained was 29% for tensile strength. This means that, at maximum, only 29% of the variation in the loss of tensile strength can be explained by the variation in the lignin content.

Statistical analysis

These data suggest that lignin content had little effect on pulp recycling potential. However, there is a possibility that the recycling potential could be affected by interactions between lignin and hemicellulose. To evaluate this possibility, a linear multiple-regression model incorporating pentosan (%) and an interaction term—pentosan $\times$ lignin—as predictors was tested against a simple regression model with pentosan as the only predictor:

Null hypothesis (H_0):

$$\text{Total change, \%} = a + b(\text{pentosan})$$

Alternative hypothesis (H_a):

$$\begin{aligned} \text{Total change, \%} = \\ a + b(\text{pentosan}) + c(\text{lignin}) \\ + d[(\text{pentosan}) \times (\text{lignin})] \end{aligned}$$

where a , b , c , and d are the regression coefficients.

Results of statistical testing on the five selected properties are listed in **Table II**. The calculated F -statistics are small, indicating a small difference between the two hypotheses. The corresponding p -values are large, so the null hypothesis cannot be rejected. That is to say, for all five selected properties, the models of null hypothesis with pentosan content as the only predictor are statistically satisfactory to describe the property changes with recycling. The model of the alternative hypothesis (including the effects of lignin,

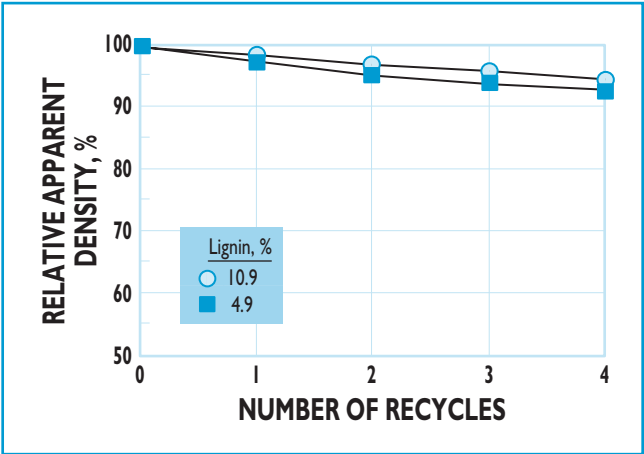
pentosan, and their interaction) is not statistically better than the model of the null hypothesis (effects of pentosan only). Therefore, the analysis shows that the influence of lignin and its interaction with pentosan on the extent of property changes with recycling is insignificant.

Effect of hemicellulose on pulp recyclability

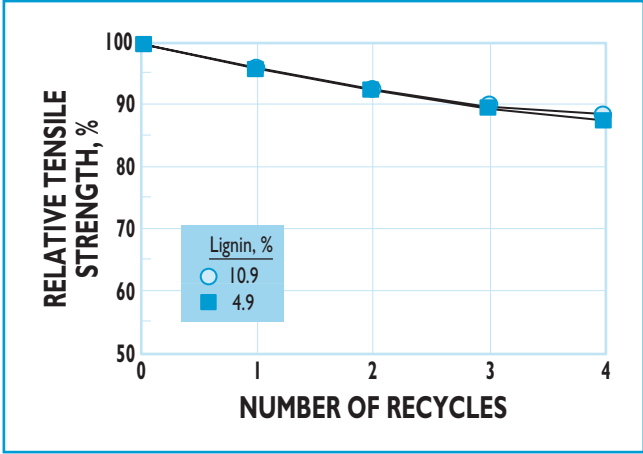
The results presented here, which separate the effects of hemicellulose and lignin on the recycling potential of hemlock pulps, confirm that hemicellulose plays a crucial role on the pulp recycling behavior. This effect was observed in both low-yield chemical pulp and ultrahigh-yield chemimechanical pulp. On the other hand, the results also suggest that lignin may not be the main factor in controlling pulp recycling behavior. This conclusion seems to contradict the often observed effects of lignin on recycled chemical pulps. However, the pulping processes for these low-yield pulps remove lignin from wood fiber with relatively low selectivity. Consequently, most of the hemicellulose is eventually removed by the end of cooking operation. This loss of hemicellulose increases the extent of loss in strength properties after recycling.

The findings from this study also serve to explain some discrepancies in the recycling behavior of several chemical pulps. It has been noted that kraft pulp loses more strength upon recycling than sulfite pulp (12), while oxygen-alkali pulp loses even more (13). The reason might be that kraft pulp retains less hemicellulose at the end of the pulping operation than sulfite pulp. Oxygen-alkali pulp is known for degradative loss of carbohydrate. Therefore, kraft and oxygen-alkali pulps have less recycling potential than sulfite pulp.

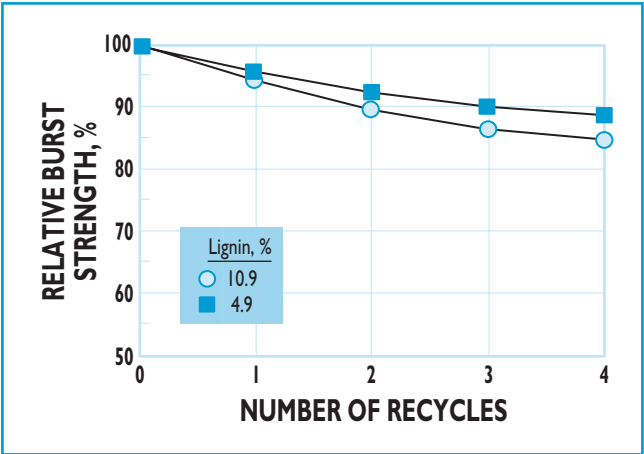
In an effort to understand the mechanism by which xylans influence the pulp recycling potential, the water-retention value (WRV) of



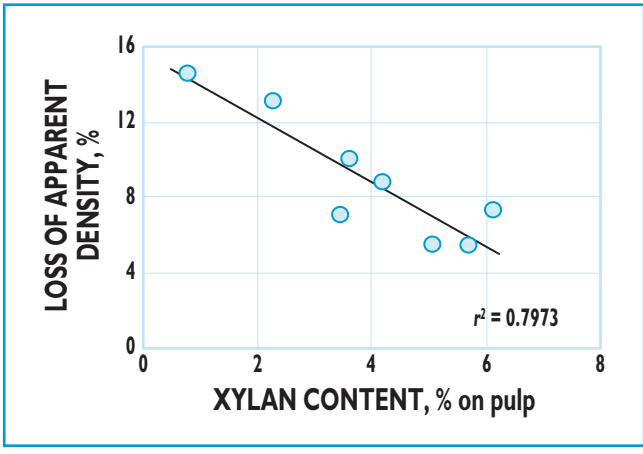
9. Changes in apparent density during recycling of Group 3 pulps (constant xylan content $\approx 6\%$; relative apparent density based on virgin pulp)



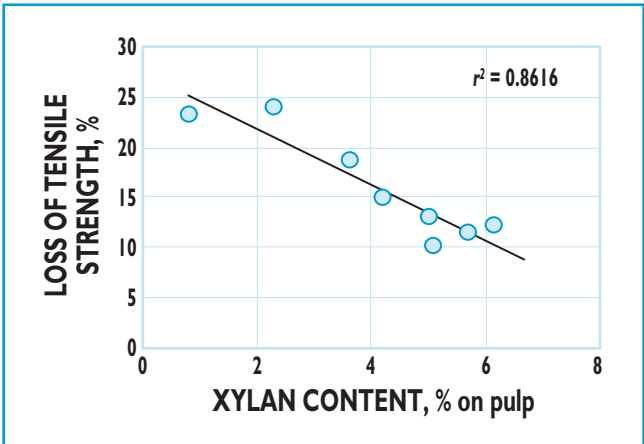
10. Changes in tensile strength during recycling of Group 3 pulps (constant xylan content $\approx 6\%$; relative tensile strength based on virgin pulp)



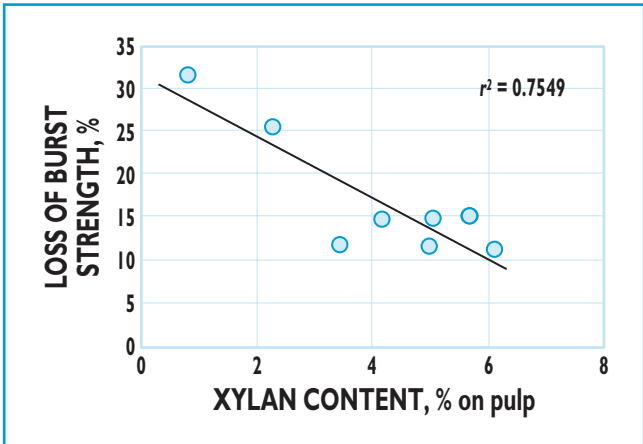
11. Changes in burst strength during recycling of Group 3 pulps (constant xylan content $\approx 6\%$; relative burst strength based on virgin pulp)



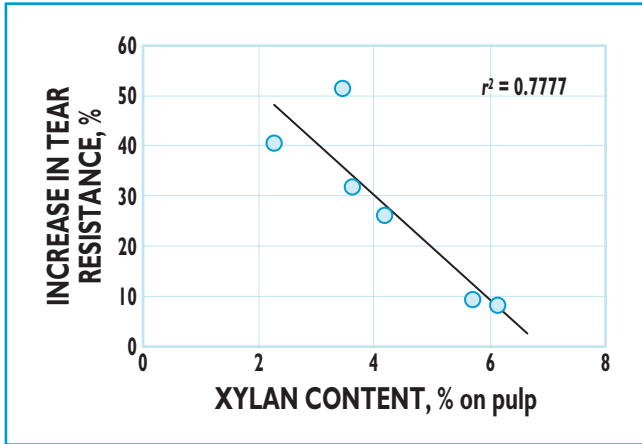
12. Percent loss of apparent density after four recycles as a function of pulp xylan content



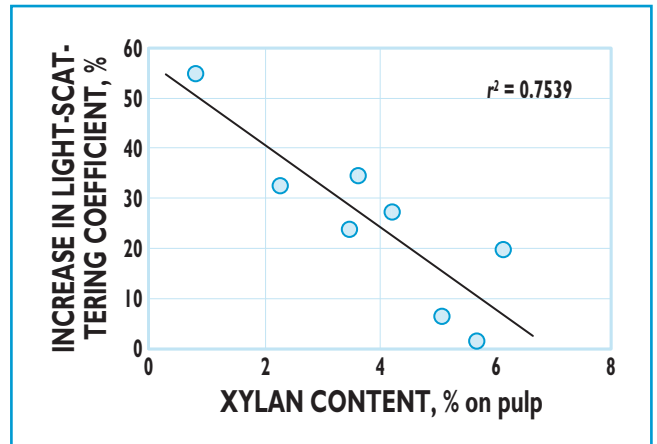
13. Percent loss of tensile strength after four recycles as a function of pulp xylan content



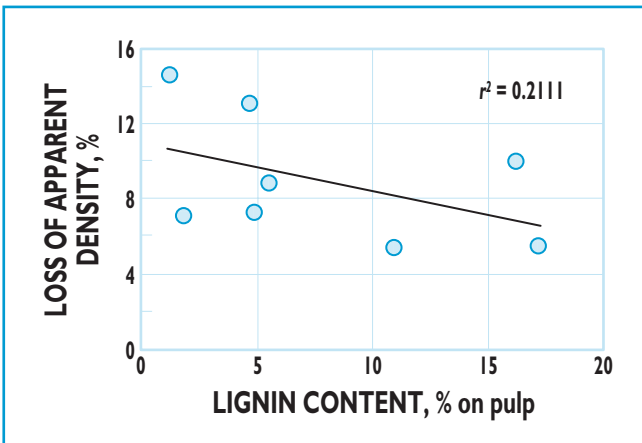
14. Percent loss of burst strength after four recycles as a function of pulp xylan content



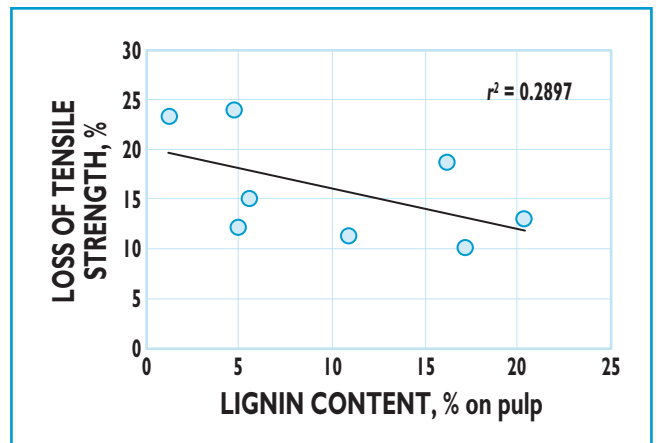
15. Percent increase in tear resistance after four recycles as a function of pulp xylan content



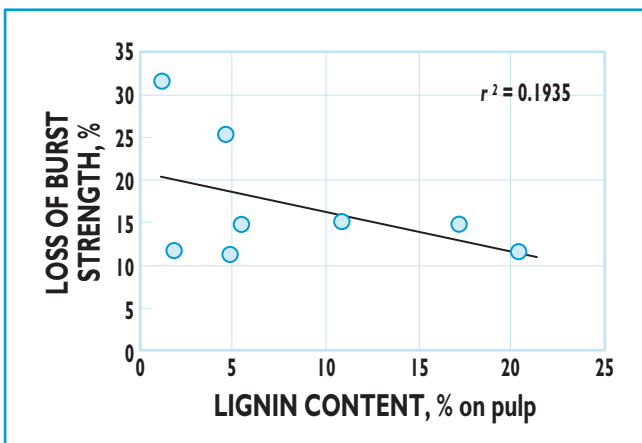
16. Percent increase in light-scattering coefficient after four recycles as a function of pulp xylan content



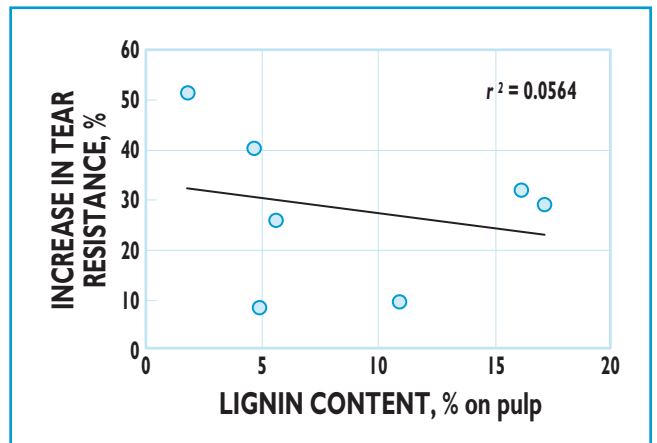
17. Percent loss of apparent density after four recycles as a function of pulp lignin content



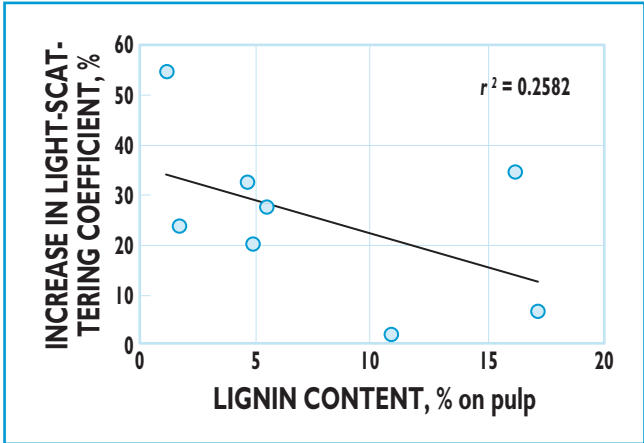
18. Percent loss of tensile strength after four recycles as a function of pulp lignin content



19. Percent loss of burst strength after four recycles as a function of pulp lignin content



20. Percent increase in tear resistance after four recycles as a function of pulp lignin content



21. Percent increase in light-scattering coefficient after four recycles as a function of pulp lignin content

virgin and recycled pulps was tested and plotted against handsheet density, as seen in Fig. 22. WRV is an indication of the degree of fiber swelling. This portion of water is physicochemically adsorbed within and on the surface of fiber cell walls (14). Most of the water molecules are adsorbed within the amorphous cellulose and hemicellulose of fibers. Hemicelluloses are of particular impor-

tance in determining the degree of swelling because of their amorphous and hydrophilic nature (9, 15, 16). The hemicellulosic material is supposed to play an important role in the fiber swelling, which in turn may influence pulp recycling behavior. However, in this study, pulp WRV did not correlate well with hemicellulose content. For example, at the same level of lignin content, pulps A, B, and C have an increasing level of pentosan content (Table I), but the WRV of the virgin pulps does not change in the same order. Thus it is difficult to explain the differences in the recycling behavior in terms of the WRV data. This is partly because WRV is affected by a variety of factors including pulping process, pulp yield, degree of beating, fines content, pH, delamination of cell wall, chemical composition, etc. The influence of these factors may offset or mask each other, creating a complicated situation. Nevertheless, for a given pulp, WRV is shown to decrease with the increasing level of recycle, indicating loss of wet-fiber flexibility upon recycling. The largest decrease occurs at the first recycle, which is the same behavior that was observed for the pulp strength properties.

Atalla (17) has pointed out that the disposition of hemicelluloses within the fiber cell wall may play a key

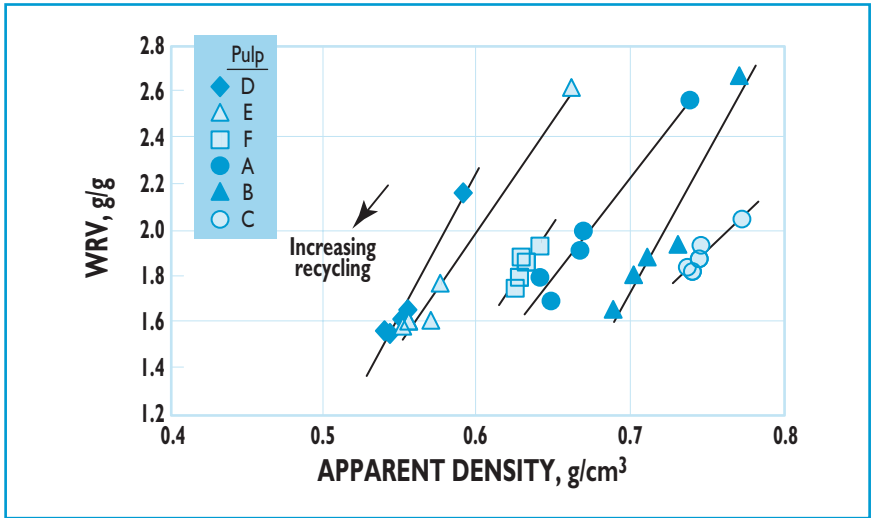
role in regulating the aggregation patterns of cellulose microfibrils within the fiber cell wall. It may well be that these hemicelluloses also play an important role in the structural organization of microfibrils during recycling. It is speculated that for the xylan-rich pulp, xylan molecules are loosely connected between cellulose microfibrils, forming a barrier between microfibrils. These microfibrils are fairly free from each other (18). Indeed, there is evidence indicating that microfibrils show a high degree of curvature around areas bridged by spokelike hemicelluloses (19).

As these pulp fibers go from a never-dried water-swollen state to a dried state, xylan molecules remain between the cellulose microfibrils and hold them against the tendency to self-associate. Consequently, the cellulose microfibrils remain relatively loose, and upon rewetting, these fibers regain their flexibility. The resultant recycled sheets maintain most of the strength properties of virgin fibers. For a pulp with low xylan content, a different mechanism is suggested. When hemicellulose

	Apparent density	Light-scattering coefficient	Tear resistance	Burst strength	Tensile strength
F-statistics	0.9779	1.0018	0.1420	0.2617	2.1322
p-value	.451	.444	.873	.782	.234
Interaction	n.s.*	n.s.*	n.s.*	n.s.*	n.s.*

*Not significant

II. Statistical test of interaction between lignin and pentosan contents



22. Water-retention value as a function of apparent density for pulp handsheets subjected to increasing levels of recycling

molecules are removed from virgin fibers, water replaces the void left by the dissolved hemicellulose. These fibers are still flexible in their water-swollen state and form sheets of high strength. However, once the fibers are dried, the microfibrils collapse together to form thicker fibrils. A strong lateral association between microfibrils is developed as a result of numerous hydrogen bonds. Consequently, fibers become stiffer, losing their papermaking potential. A significant portion of the fiber's strength properties are lost during the subsequent recycle.

Different from xylan, glucomannan has a stronger affinity with cellulose microfibrils and may even form a crystallized zone with cellulose. It is also known that glucomannan is much more effective in contributing to fiber bonding than xylan (20), which partly accounts for the greater strength of papers made from softwood pulps compared with those made from hardwood pulps (21). It would be interesting to see how glucomannan affects the changes in physical properties of recycled pulp. Further elucidation of the mechanism by which xylan and glucomannan influence pulp recycling potential should shed new light

on fiber "hornification" (9), the mechanism of which is still not fully understood.

The effect of xylan on pulp recyclability, as demonstrated in this study, reveals new possibilities for improving the recyclability of low-yield chemical pulps, which have traditionally been considered to have poor recycling potential. If pulping processes can be tailored to incorporate more xylan and other hemicellulose in the pulp, it would improve the pulp recyclability as well as its overall strength.

CONCLUSIONS

The amount of pentosan (mainly xylan) in fibers plays a crucial role on the recycling potential of hemlock pulps. In contrast, the lignin content has only a small effect on the recycling potential of the pulps. The effect of xylan in preserving pulp properties during recycling was observed in both low-yield chemical pulps and high-yield chemimechanical pulps.

The magnitude of property changes after recycling was shown to correlate linearly with pulp xylan content for the pulps used in this study. On the other hand, lignin content did not show any meaningful

correlation with the magnitude of property changes. Statistical analysis indicates that the property changes on recycling can be well explained by pentosan content alone, since lignin content and the interaction between pentosan and lignin did not show any significant influence.

It is speculated that the presence of xylan molecules in between cellulose microfibrils prevents neighboring microfibrils from developing close associations with each other during drying. By doing so, the xylan helps to preserve much of the fiber's wet flexibility, which is crucial if the fiber is to maintain its papermaking properties when it is recycled. **TJ**

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LITERATURE CITED

- Chatterjee, A., Lee, J., Roy, D. N., et al., *1991 International Paper Physics Conference Proceedings*, TAPPI PRESS, Atlanta, p. 129.
- Lundberg, R. and de Ruvo, A., *Papier Carton Cellulose* 71(1): 75(1980).
- Minor, J. L. and Atalla, R. H., *MRS Symposium Proceedings*, Vol. 266, Materials Research Society, Pittsburgh, 1992, p. 215.
- Scallan, A. M. and Tigerstrom, A. C., *1st Research Forum on Recycling*, CPPA, Montreal, 1991, p. 149.
- Klungness, J. H. and Caulfield, D. F., *Tappi J.* 65(12): 94(1982).
- Lundberg, R. and de Ruvo, A., *Svensk Papperstid.* 81(8): 266(1978).
- Gallay, W., *Transactions of the Symposium on Fundamentals of Papermaking Fibers*, British Paper and Board Makers Association, London, 1958, p. 377.
- Eastwood, F. G. and Clarke, B., in *Fiber-Water Interactions in Papermaking*, Vol. II, British Paper and Board Makers Association, London, 1978, p. 835.
- Giertz, H. W., in *Formation and Structure of Paper* (F. Bolam, Ed.), Vol. 2, British Paper and Board Makers Association, London, 1962, p. 597.
- Cao, B., Tschirner, U., Ramaswamy, S., et al., *TAPPI J.* 80(9): 193(1997).
- Penniman, J. G., *Paper Trade J.* May 30: 44(1981).
- Bovin, A., Hartler, N., and Teder, A., *Paper Technol.* 14(5): 261(1973).
- Marton, R., Brown, A., Granzow, S., et al., *Progr. Paper Recycling* 3(1): 58(1993).
- Stamm, A. J., *Wood and Cellulose Science*, Ronald Press, New York, 1964, p. 163.
- Young, G. H. and Rowland, B. N., *Paper Trade J.* 97(15): 44(1933).
- Lyne, L. M. and Gallay, W., *Tappi* 33(9): 429(1950).
- Atalla, R. H., Hachney, J. M., Uhlin, I., et al., *Intern. J. Biol. Macromol.* 15: 109(1993).
- Ranby, B. G., in *Fundamentals of Papermaking Fibers* (F. Bolam, Ed.), British Paper and Board Makers Association, London, 1958, p. 55.
- McCann, M. C., Wells, B., and Roberts, K., *J. Cellulose Sci.* 96: 323(1990).
- Robinson, J. V., in *Pulp and Paper, Chemistry and Chemical Technology* (J. P. Casey, Ed.), Vol. 2, John Wiley & Sons, New York, 1980, p. 943.
- Jones, K. G. and Rieth, E., *Wochbl. Papierfabr.* 68: 853(1933).