Variability in pulping and fiber characteristics of hybrid poplar trees due to their genetic makeup, environmental factors, and tree age

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ABSTRACT

The variability in fiber and pulping characteristics caused by the genetic makeup of five hybrid poplar clones was investigated. Specific gravity for the five varied from 0.30 to 0.36. Pulp yield varied significantly (49–57%). Variation in pulp yield correlated well with the alpha-cellulose content of the wood. However, higher yield did not always translate into higher pulp production due to differences in specific gravity (digester packing).

Strength properties (tear and tensile) also varied significantly among clones. The drier and warmer growing environment found in northeast Oregon, where irrigation was required, yielded trees with slightly longer fibers and higher specific gravities and pulp yields (3–4%) compared to trees of the same clone grown in the cooler, wetter environment typical of western Oregon. The effect of tree age was investigated by separating and characterizing wood from each annual ring. Fiber length and pulp yield increased with age, as did tear index at a given tensile index.

Application:

Selecting a clone with higher wood specific gravity and pulp yield will result in higher pulp production in a mill. Evaluation of fiber characteristics at different ages will help determine the optimum harvest time for these clones.

While the supply of wood in the Pacific Northwest is abundant, availability of this supply is becoming problematic due to reduced harvesting on federal lands (1). This has prompted a search for alternate fiber sources. Short-rotation hybrid poplar is a viable source for clonal propagation. It would be an additional and a uniform source of fiber. Most of the clonal propagation efforts on plantation hybrid poplar have been oriented toward biomass production. However, if this source of fiber is to be used for pulp production, it is equally important to look at chemical and pulping characteristics before making a selection for clonal propagation.

It is widely reported in the literature that significant variation in physical and chemical composition exists among hybrid poplar clones. Several researchers *(2, 3)* have demonstrated that genetic makeup can influence fiber characteristics and the specific gravity of the tree. Both of these properties can influence the quantity as well as the quality of the pulp. It has also been reported that genetic makeup influences the chemical composition as well as the physical properties *(4-6).* These investigators found alpha-cellulose contents of 40–53%, which would result in pulp yield differences. Environmental factors, cultural practices, and tree age may further influence the fiber and pulping properties of hybrid poplar trees. The objective of this work was to investigate the variability in fiber and pulping characteristics among clones caused by these factors.

EXPERIMENTAL

Raw materials

Four year old trees from a plantation in eastern Oregon were obtained. These trees were debarked and chipped in a laboratory chipper. The accepts (2–8 mm chip thickness fraction) were used for kraft pulping. Discs taken at breast height were used to measure the specific gravity according to TAPPI Test Method T 258 om-94. Packing factors were determined by weighing the amount of screened chips that would fit into a 1 ft^3 container.

Fiber length and coarseness were determined using a Kajaani FS-100 fiber length analyzer. Trees of the same clone were grown in both east-side and west side locations (relative to the Cascade Mountains) of Oregon. The east side location has a drier and warmer climate that requires supplemental irrigation to support optimal growth. West side trees were grown in a moist, cool environment where supplemental irrigation and fertilization were not required. An 8 year-old tree was used to study the effect of age on wood properties. The wood from annual rings 1 through 4 was combined. The wood from annual rings 5, 6, 7, and 8 was processed individually.

Kraft pulping

Kraft pulps were prepared in a conventional lab digester. Pulping conditions, which were held constant, were as follows:

- 16% active alkali
- 25% sulfidity
- 4:1 liquor-to-wood ratio
- 172°C pulping temperature
- 1200 H-factor.

At the end of each cook, the chips were defiberized in a mix tank

Clone	Specific gravity	Packing factor, lb/ft³	Screened yield, %	Production per 4000 ft³ digester, a.d. tons pulp	Kappa number	Fiber length, mm
1	0.30	10.5	49.1	10.3	14.9	0.76
2	0.31	9.7	57.0	11.1	11.3	0.70
3	0.33	9.9	56.2	11.1	11.4	0.72
4	0.32	10.5	51.5	10.8	13.4	0.91
5	0.36	11.4	56.1	12.8	13.8	0.91

I. Physical properties and pulping results of trees from five different clones

Clone	Extractive content, %	Klason lignin[a], %	Holo-cellulose[a], %	Alpha-cellulose[a], %	Hemi-cellulose[a] %
1	1.7	20.3	73.8	40.3	32.5
2	ND[b]	24.0	76.1	51.7	20.1
3	ND	26.4	78.8	52.5	24.4
4	1.4	20.5	81.0	45.8	35.3
5	3.1	16.6	85.7	51.2	34.6

[a]Based on extractive-free o.d. wood basis
[b]Not determined

II. Chemical composition of the clones

equipped with a Lightnin'® mixer. The pulp was thoroughly washed, screened and centrifuged. Yield and kappa number (using TAPPI Test Method T 236) were determined for these pulps.

Chemical analysis

Extractive contents of the wood were measured by extracting wood meal (passing through a 20-mesh screen) with acetone in a Soxhlet apparatus for 24 hours. Other chemical analyses were performed on extractive free wood. Klason lignin was determined according to TAPPI Test Method T 222 om-88, modified so that the sample size was reduced to 0.5 g with all other quantities reduced correspondingly. The alpha-cellulose contents were determined by a slightly modified version of Browning's method *(7)*. Holocellulose was prepared using the acid chlorite method described by Browning *(8)*.

RESULTS AND DISCUSSION

Fiber and pulping characteristics

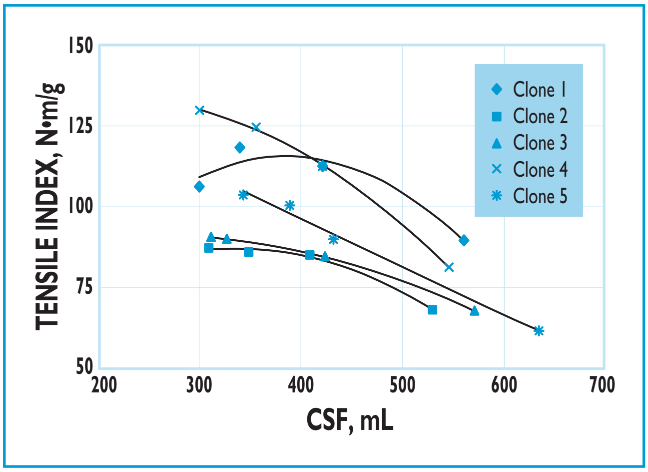
Pulp production is not only influenced by pulp yield but also by the physical properties of the pulp wood. **Table I** summarizes the physical properties and pulping results of five different clones grown under identical conditions. The specific gravity of these clones was 0.30–0.36. Four clones have rather similar specific gravity. The fifth has a significantly higher specific gravity and consequently a higher packing factor.

The impact of specific gravity becomes more clear when pulp production for a given digester volume is computed, factoring in the pulp yield. Clone 5, for example, would yield 12.8 tons of pulp per 4000 ft³ of digester (packing factor × 4000 ft³ × yield/2000 = tons per 4000 ft³ digester). Clone 2 has a slightly higher pulp yield but results in almost 2 tons less pulp per digester due to its lower specific gravity and lower packing factor. These differences can make a large difference in the total daily production of a mill.

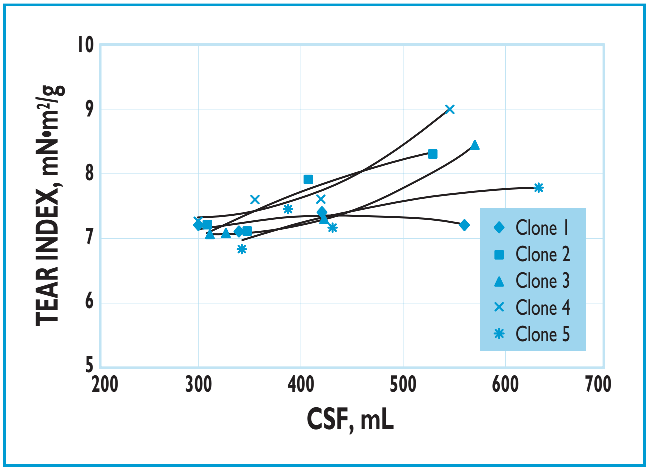
Under identical pulping conditions, the kappa number of the pulps from the clones varied from 11.3 to 14.9. These results suggest that clones 2 and 3 are easier to delignify compared to clone 1. To seek an explanation for differences in delignification, the clones were analyzed for their chemical composition (**Table II**). The rate of delignification appears to be independent of the Klason lignin content. Clones 2 and 3 have the lowest kappa number, yet their lignin contents are 24 and 26.4%, respectively. The higher rate of delignification observed by Mortha *et al. (9)* for hybrid poplar was explained by the fact that a lower specific gravity minimizes the diffusion limitations of lignin out of the wood chips. Present data do not support that hypothesis. The lowest specific gravity clone (no. 1) produces pulp with the highest kappa number.

Another explanation could be that the lignin structure of these clones is different. Nimz *(10)* reported that β-0-4 linkages in guaiacyl units are hydrolyzed at a slower rate than syringyl units. A straight line correlation between delignification rate and the ratio of syringyl to guaiacyl propane units was also obtained by Chang and Sarkanen *(11)*. Since the syringyl content of a typical hardwood can vary from 20 to 60% *(12)*, the higher rate of delignification is most likely due to higher syringyl contents in the native lignin of clones 2 and 3.

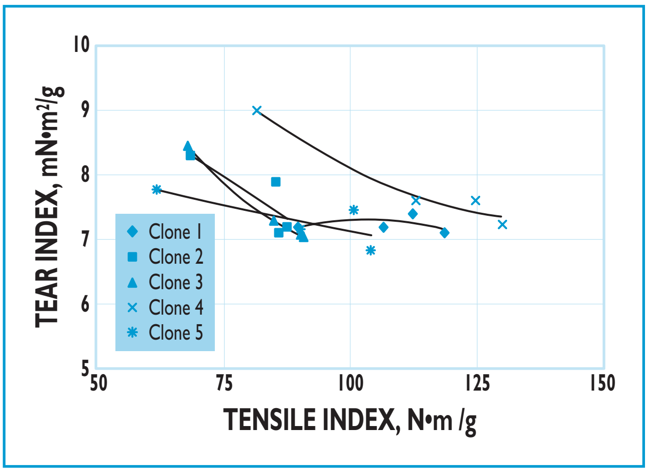
These clones also exhibited a wide range of pulp yield (49–57%). Similar variations in pulp yield for hybrid poplar and eucalyptus were reported by Jamye *(4)* and Zobel *(13)*, respectively. The reason for the pulp yield differences could be due to the alpha-cellulose content of the



1. Hybrid poplar clone comparison



2. Hybrid poplar clone comparison



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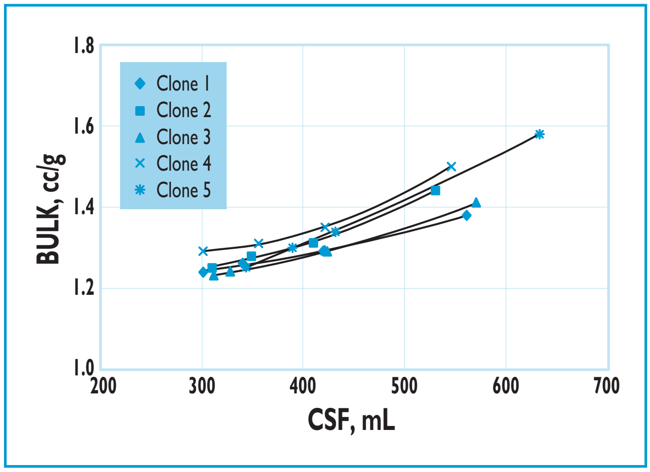


4. Hybrid poplar clone comparison

wood. It has been demonstrated that kraft pulp yield is directly proportional to the alpha-cellulose content of the wood *(14)*. The results in Tables I and II show a similar relationship between pulp yield and alpha-cellulose content.

Strength properties

Depending on the end use of the pulp, the strength properties of a pulp might also play a significant role in selection criteria. Various strength properties for these clones are presented in **Figs. 1–4.** A significant difference exists in tensile index at a given freeness among clones. The tensile index of clone 4 is almost 30% higher compared to clones 2 and 3 (Fig. 1).

The tear index at a given freeness or tensile index also showed a large variation among clones (Figs. 2 and 3). The higher tear and tensile indexes for clone 4 could be due to longer fiber lengths; however, clone 5 had a similar fiber length, yet its tear and tensile values were significantly lower than those of clone 4. Bulk properties of unrefined pulps were different, but upon refining, these pulps had very similar bulk values (Fig. 4). The difference in fiber length could not account for all the differences seen in some of the strength properties of the clones.

Trial	Specific gravity	Kappa number	Yield, %	Wgt. avg. fiber length, mm
1	0.28	14.7	55.1	0.83
2	0.29	15.2	55.8	0.86

III. Properties of two trees from the same clone and the same environmental conditions

From the foregoing sections, we conclude that significant differences exist in fiber, pulping, and strength characteristics among these clones. However, it is not clear whether these differences are caused by genetic

Clone	Specific gravity	Tight packing factor, lb/ft³	Screened yield, %	Production per 4000-ft³ digester, a.d. tons pulp	Kappa number	Weight-weighted fiber length, mm
4[a]	0.32	10.5	51.5	10.8	13.4	0.91
4[b]	0.27	9.0	50.5	9.1	12.8	0.75
5[a]	0.36	11.4	56.1	12.8	13.8	0.91
5[b]	0.29	9.6	53.3	10.2	14.7	0.83

[a]East side
[b]West side

IV. Pulping results: trees grown east or west of the Cascade range

Clone	Extractive content, %	Klason lignin[a], %	Holo-cellulose[a], %	Alpha-cellulose[a], %	Hemi-cellulose[a] %
4[b]	1.48	20.46	81.0	45.7	35.3
4[c]	2.88	20.40	83.8	44.6	39.2
5[b]	3.05	16.55	85.7	51.2	34.6
5[c]	2.85	15.46	84.6	49.5	35.1

[a]Reported on an extractive-free wood basis
[b]East side
[c]West side

V. Chemical composition of clones—east and west side of the Cascade Mountains

makeup or are due to tree-to-tree variation. To differentiate between these factors, two trees from the same clone were characterized.

We found that the fiber, pulping, and strength properties of these two trees were virtually identical (**Table III**). This suggests that the genetic makeup of the clone has the primary influence on these characteristics.

Effect of environment and cultural practices

To investigate the effect of environment, trees having the same genetic makeup but grown at two different locations in Oregon (east and west of the Cascade Mountains) were obtained. A comparison of the fiber and pulping results for two clones grown under differing conditions is given in **Table IV.** For both the clones studied, trees grown under the drier, warmer climate with drip irrigation (east side) had higher specific gravity, higher pulp yield, and slightly longer fibers. The higher specific gravity and pulp yield would have the same implications for production as described in the earlier section.

Snook *et al. (15)* also reported higher pulp yield for irrigated sites. However, based on statistical analysis, they concluded that no significant differences in pulp yield between irrigated and control sites were observed. In the Snook study, the pulping conditions used (20.6% active alkali with approximately a 2400 H-factor) were much harsher than typically used for hardwoods. Thus it is likely that, due to the much harsher pulping conditions, the extent of carbohydrate degradation was such that the yield differences could not be distinguished statistically between irrigated and control sites. Due to the harsh pulping conditions in the Snook study, differences in strength properties among various sites may also not have been detected.

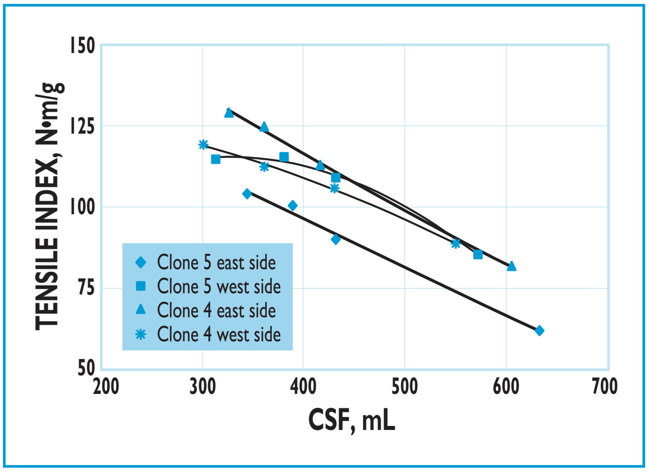
The chemical composition of the trees grown on the east and west sides was found to be similar (**Table V**) except for the consistently higher alpha-cellulose content for east side trees. Once again, higher alpha-cellulose contents would account for higher pulp yield from east side trees. The influence from genetic makeup is also apparent under the different environmental conditions.

The strength properties do not show any trend with regard to location of the tree. For example, the tensile index of the pulp at a given freeness for east side clone 5 is slightly lower compared to west side clone 5, whereas the tensile index of east side clone 4 is slightly higher compared to west side clone 4 (**Fig. 5**).

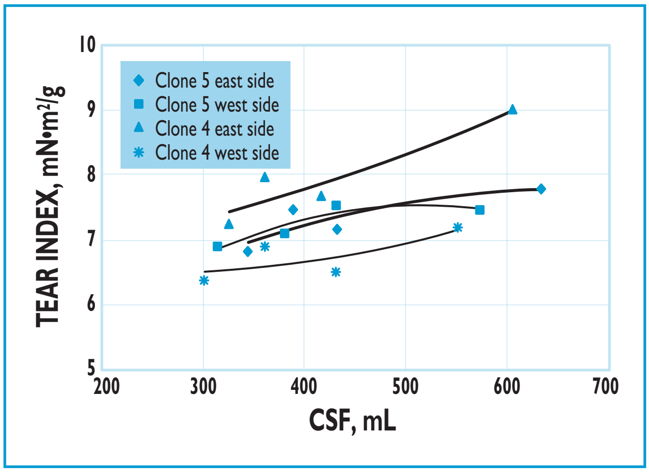
The clone 5 tear index is not affected by environmental factors. The tear index at a given freeness and the tear index at a given tensile for the east side sample of clone 4 are approximately 15–20% higher compared to those from the west side (**Figs. 6 and 7**). The higher tensile and tear for the east side clone 4 could be due to its significantly higher fiber length (Table IV). For clone 5, although the fibers of the east side sample are slightly longer, this may not be enough to account for the difference in strength properties. East side clones definitely produce pulp with higher bulk (**Fig. 8**); this might have a significant impact on papermaking properties. It is not yet understood how environment and cultural practices can change the physiological activities of a tree to influence its pulping and fiber characteristics.

Effect of age

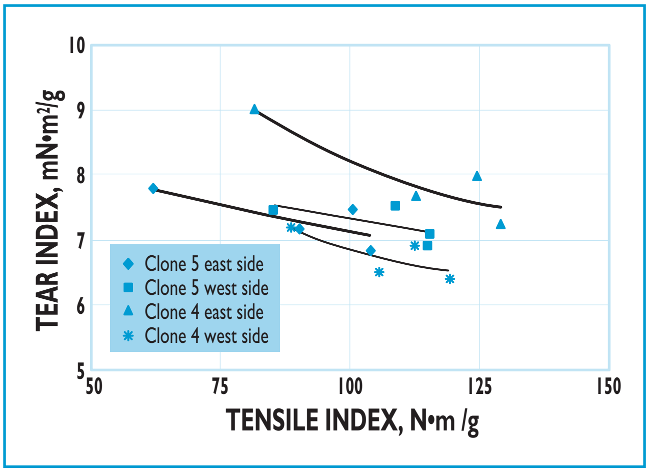
Plantation trees, because of their short rotation time, may contain a significant amount of juvenile wood. The juvenile wood might affect papermaking properties and could



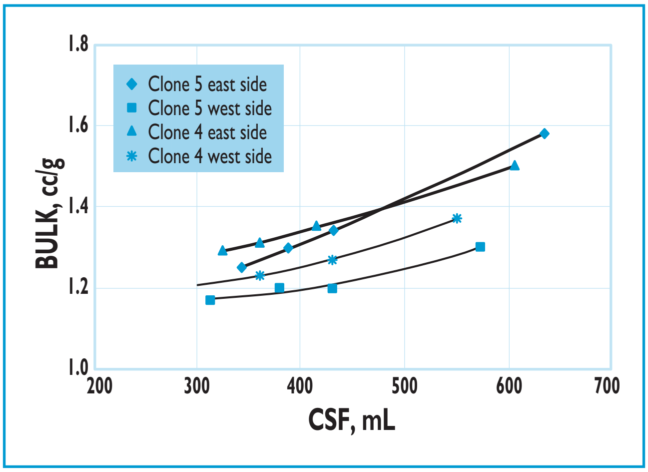
5. Hybrid poplar east and west sides of the Cascades



6. Hybrid poplar east and west sides of the Cascades



7. Hybrid poplar east and west sides of the Cascades



8. Hybrid poplar east and west sides of the Cascades

have an impact on the optimum harvest time.

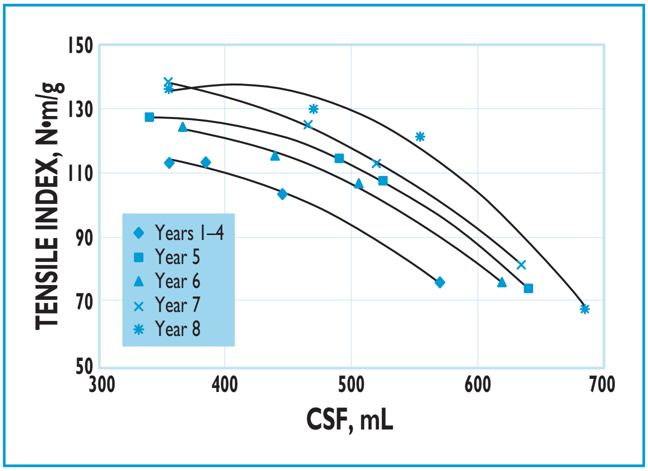
Wood density and fiber measurements are presented in **Table VI.** It is evident that fiber length increases with the tree age, while specific gravity shows a gradual decline. Fiber coarseness shows no clear correlation with tree age. These results are in good agreement with Cisneros *et al. (16),* who reported similar changes in fiber properties of hybrid poplar clones. Boyce *(2)* also found that the length of the fiber increased with the number of rings from the pith and with the diameter of the tree. In his work, the fiber length varied from 0.70 to 1.38 mm.

The tensile index increases with the tree age. At 400 mL CSF, the tensile of pulp from the eighth annual ring is approximately 20% higher than pulp from 1-4-annual-ring wood (**Fig. 9**). The tear index of unrefined pulp also increases with age, probably due to greater fiber length, but with refining, the tear indices of these pulps approach a similar value (**Fig. 10**).

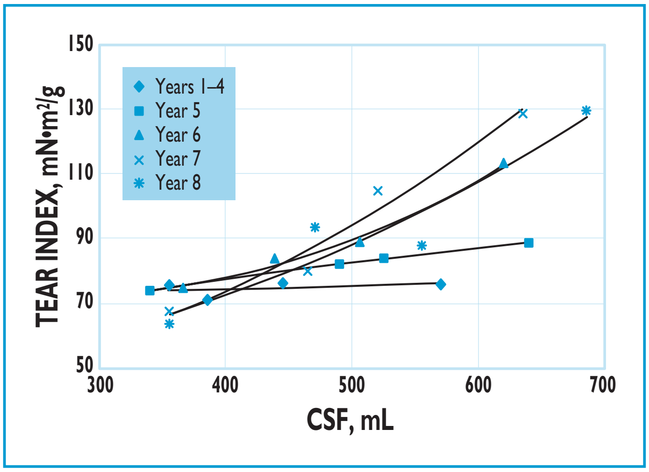
A plot of tear vs. tensile index shows that tear index at a given tensile tends to level off after the sev-

Growth ring	Specific gravity	Weight-weighted fiber length, mm	Coarseness, mg/100 m
1–4	0.27	0.69	8.7
5	0.27	0.90	10.1
6	0.25	0.89	9.7
7	0.26	0.96	9.2
8	0.23	1.09	10.3

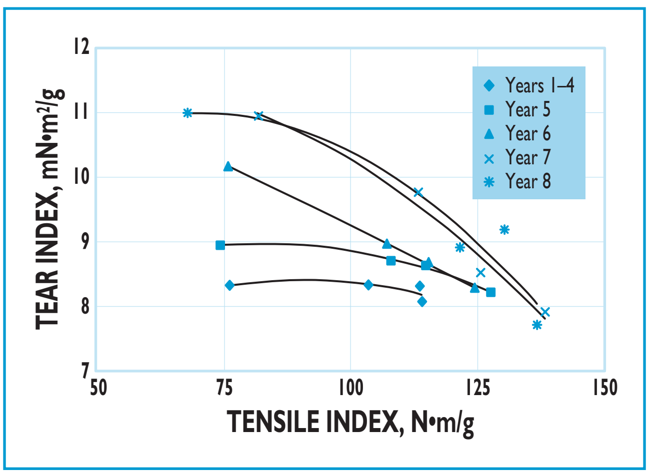
VI. Wood and fiber characteristics of various annual rings of an 8 year old tree



9. Hybrid poplar—growth rings



10. Hybrid poplar—growth rings



11. Hybrid poplar—growth rings

enth year (**Fig. 11**). This suggests that after 7–8 years, the papermaking properties may not change significantly. This conclusion can further be corroborated by the fact that once the trees are 8 years old, the amount of wood with longer fiber (0.9 mm and longer) is approximately four times in volume compared to the wood containing shorter fiber (0.7 mm). An earlier study by Zarges *et al. (17)* also concluded that the papermaking properties of a 7 year old plantation *Populus* tree were as good, if not better, than those of a mature *Populus* tree.

Hatton *(18)* has done extensive work separating the properties of juvenile wood from mature wood. However, the focus here is to evaluate the papermaking properties of a whole tree at a certain age rather than to separate the juvenile from the mature wood.

CONCLUSIONS

We reached the following conclusions based on our research:

- The five hybrid clones investigated showed large variations in specific gravity and pulp yield, which could significantly affect pulp production.
- Variations in pulp yield could be explained by corresponding variations in the alpha-cellulose content of these clones.
- Significant differences were also observed in the strength properties of these clones. Tear-tensile relationships could not always be explained by fiber length alone.
- Irrigated clones grown in a drier, warmer climate had higher specific gravity, higher pulp yields, and slightly longer fiber lengths and provided pulps with higher bulk.
- Fiber length and tensile and tear indexes increased with the tree age. As the tree becomes older, the juvenile wood (shorter fiber) constituted a lower percentage of the total volume. Therefore, the impact from juvenile wood diminishes with age.

TJ

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