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# Small-Diameter Trees Used for Chemithermo-mechanical Pulps


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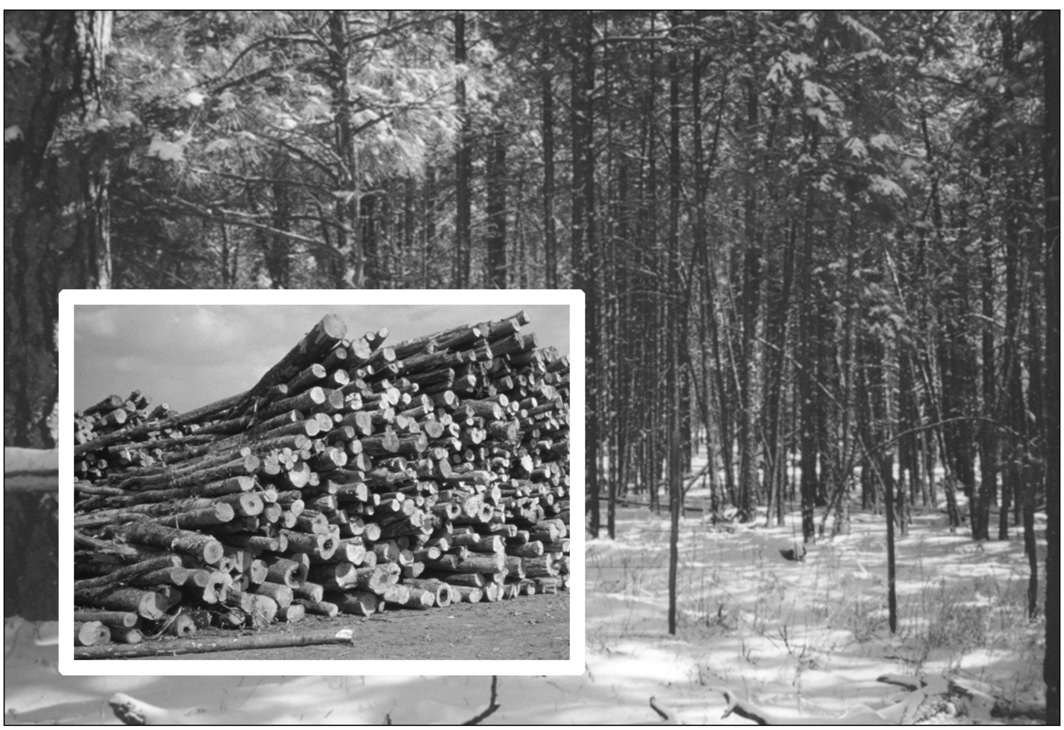

# Abstract

To restore and maintain forest ecosystem health and function in the western interior of the United States, many small-diameter stems need to be removed from densely stocked stands. In general, these materials are underutilized. Information on the properties of these resources is needed to help forest managers understand when timber sales are a viable option to accomplish ecosystem management objectives. Providing proof that this small-diameter material yields quality pulp would help increase its value and therefore help remove it from the forest. This study examines the acceptability of the small-diameter resource as a raw material for high-yield chemithermomechanical pulping (CTMP), which has the potential for improved fiber characteristics and paper strength compared with those of thermomechanical pulping (TMP). Pulps using CTMP were prepared from lodgepole pine and mixed Douglas-fir/western larch sawmill residue chips; lodgepole pine, Douglas-fir, and western larch submerchantable logs; and lodgepole pine, Douglas-fir, and western larch small trees. These small-diameter pulps were compared with commercially obtained sawmill residue chips of a Douglas-fir/western larch mixture and lodgepole pine. These pulps were also evaluated to see if CTMP improved the properties of the final product compared with products made using TMP. Compared with the controls, the CTMP prepared from Douglas-fir and lodgepole pine small trees and Douglas-fir submerchantable logs consumed more electrical energy during pulp preparation and had higher paper strength properties and lower optical properties. Also compared with the controls, lodgepole pine submerchantable logs consumed about the same electrical energy and had marginal strength properties and higher optical properties. Western larch submerchantable logs and small trees had the lowest electrical energy consumption of all pulps tested, low strength properties, but some of the higher optical properties. Western larch submerchantable logs and small trees appear to be unsuitable for CTMP. For the majority of the materials, CTMP improved the properties of the final product compared with corresponding TMP.



Keywords: western softwoods, lodgepole pine, Douglas-fir, western larch, small-diameter trees, mechanical pulping, chemithermomechanical pulping, CTMP, pulp properties, paper properties



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## Introduction

The focus of forest management on public lands has taken on a more ecological orientation during the past decade (USDA–USDI 1994, 1997; Iverson and others 1996). Currently, forests in the western United States are suffering from lack of diversity at the landscape level, the potential for large-scale disturbances such as insect infestations and fire, and the need for functional late-succession stand structures within watersheds. The extreme fires losses of 2000 and 2002 have emphasized the serious conditions in many forests. In some cases, active management will be required to restore healthy forests.

Landscape level manipulations can be expensive, and funding for these activities must compete with other priorities in Federal and State budgets that may have nothing to do with forest management. Accordingly, whenever possible, public land managers use timber sales to fund management activities. The land management focus has turned more toward ecological objectives rather than strictly timber production. In practice, this means that State and Federal land managers will offer a different type of material for sale than they would have under a program oriented more toward timber production. This material is often smaller in diameter than the traditional resource (Colville National Forest 1994). Also, forest operations required to meet ecosystem objectives are often complex and specify equipment with which operators may have relatively little experience. Oftentimes, the size of the resource and the complexity of the treatments combine to limit the economic feasibility of the proposed treatments (Barbour and others 1995, Spelter and others 1996). Managers often find themselves in situations were timber sales being offered do not cover costs, fail to meet the ecological objective, or fail to attract bidders.

The USDA Forest Service has instituted a program to help public land managers understand the complexity and economic difficulty of integrating biological, ecological, silvicultural, and social objectives in a climate where management activities must be self-supporting (Skog and others 1995, Barbour and Skog 1997). Previous research (Barbour and Skog 1997, Myers and others 1999a,b) and this study are part of that program. Many of the trees removed under ecosystem management treatments are small diameter, that is, less than 254 mm at breast height. Therefore, pulp is a logical use for them. Providing proof that quality pulp can be produced from this small-diameter material would help increase its value and therefore help remove it from the forest. This study examines the small-diameter resource as a raw material for high-yield chemithermomechanical pulping (CTMP), which has the potential for improved fiber characteristics and paper strength compared with those of thermomechanical pulping (TMP) (Leask 1987). Such information will help entrepreneurs and corporations make better-informed decisions about bidding on marginal sales offered by public land managers. Another objective of the Federal program is to help public land managers understand the economic viability of the sales they design and enable them to offer sales that are more attractive to potential bidders while still achieving their ecological objectives.

## Experimental

### Raw Materials

All raw materials used in this study were obtained from the Colville National Forest (eastern Washington) or the Idaho Panhandle National Forest (northern Idaho). The species selected were Douglas-fir [*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco], lodgepole pine (*Pinus contorta* Dougl. Ex Loud.), and western larch (*Larix occidentalis* Nutt.). A Douglas-fir/western larch mixture of sawmill residue chips (SRC) and lodgepole pine SRC were obtained commercially from Vaagen Bros. Lumber (Colville, Washington) and used as controls representing raw materials currently used for pulping. The submerchantable logs (SML) had small-end diameters of less than 89 mm and were primarily treetops. The small trees (ST) had less than a 127-mm diameter at breast height and were the entire tree.

These small-diameter resources were not removed from young, vigorously growing stands with a high content of juvenile wood (Zobel and van Buijtenen 1989, p. 82–100). They were from densely stocked stands, typically 70 or more years old, where crowded growing conditions limited diameter growth. Consequently, juvenile wood was not an issue. All chips and logs were shipped to the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wisconsin, for additional processing.

Logs were hand peeled at FPL to remove all bark and chipped to 19 mm long in a four-knife commercial-sized chipper. A disk was cut from the end of each log after peeling and before chipping, for specific gravity determination according to TAPPI Test Method T258, using ovendry weight and maximum volume. Chipped logs and SRC were screened to remove all particles greater than 38 mm long and less than 6 mm long. Screened chips were thoroughly mixed in a large V-mixer, weighed into 4- or 5-kg samples, placed in polyethylene bags, and stored at 4°C until used for pulping. Chip solids content was determined after mixing and bagging by ovendrying three chip samples of each raw material to remove all moisture and then recording the average.

# CTMP Preparation

Although several procedures could have been chosen for preparing CTMP, chemical impregnation followed by pressurized fiberization was selected because of equipment availability within our laboratory. To eliminate an experimental variable, an identical sodium sulfite impregnation procedure was followed for all raw materials, aiming for a 3.5% application level. Each batch of moist wood chips was placed in a perforated basket that fit inside a 23-L stationary pulp digester. The chips were heated in 138-kPa saturated steam for 20 min, commencing when the digester internal pressure stabilized. After pressure relief, the perforated basket and heated chips were removed from the digester and lowered into a tank that contained a sodium sulfite solution. Chips were completely covered with the liquor and soaked for 30 min. Convection currents kept the liquor circulating through the chip basket and eliminated the need for stirring. Chips were removed from the liquor and allowed to drain 5 min before fiberization. The volume of liquor absorbed by the wood chips was measured. Sodium sulfite treatment level was calculated from volume of liquor absorbed by the wood chips, liquor sodium sulfite concentration, and ovendry weight of wood chips (Table 1). The chemical impregnation procedure and pressurized and atmospheric disk refiner

**Table 1—Chip solids content, liquor impregnation, and refining pass information**

| Input material[a] | Wood specific gravity | Chip solids content (%) | $Na_2SO_3$ concentration in liquor (g/L) | Liquor adsorbed by chips (mg $Na_2SO_3$ per OD[b] g of wood) | $Na_2SO_3$ treatment (%) | Range of refiner plate gap settings (mm) | Refining passes[c] |
|---|---|---|---|---|---|---|---|
| **Constant liquor concentration** | | | | | | | |
| Lodgepole pine SML | 0.417 | 79.4 | 49.0 | 75.6 | 7.7 | 0.305–0.127 | 7 |
| Lodgepole pine ST | 0.430 | 62.8 | 49.0 | 52.0 | 5.2 | 0.305–0.102 | 6 |
| Lodgepole pine SRC | 0.410 | 42.7 | 49.0 | 32.3 | 3.2 | 0.305–0.152 | 5 |
| Douglas-fir SML | 0.426 | 74.0 | 49.0 | 54.3 | 5.4 | 0.305–0.127 | 5 |
| Douglas-fir ST | 0.458 | 69.0 | 49.0 | 46.8 | 4.7 | 0.305–0.152 | 6 |
| Western larch SML | 0.483 | 78.8 | 49.0 | 52.1 | 5.2 | 0.305–0.102 | 6 |
| Western larch ST | 0.490 | 61.9 | 49.0 | 40.1 | 4.0 | 0.305–0.152 | 6 |
| Douglas-fir / western larch SRC | 0.500 | 51.0 | 49.0 | 26.3 | 2.6 | 0.356–0.178 | 5 |
| **Variable liquor concentration** | | | | | | | |
| Lodgepole pine SML | 0.417 | 79.0 | 32.0 | 36.8 | 3.7 | 0.356–0.102 | 5 |
| Lodgepole pine ST | 0.430 | 61.3 | 26.5 | 28.1 | 2.8 | 0.356–0.102 | 5 |
| Lodgepole pine SRC | 0.410 | 41.4 | 48.6 | 38.4 | 3.8 | 0.356–0.102 | 5 |
| Douglas-fir SML | 0.426 | 78.4 | 25.3 | 32.7 | 3.0 | 0.356–0.102 | 5 |
| Douglas-fir ST | 0.458 | 69.0 | 36.7 | 35.7 | 3.6 | 0.356–0.102 | 5 |
| Western larch SML | 0.483 | 78.8 | 32.9 | 33.8 | 3.4 | 0.356–0.152 | 5 |
| Douglas-fir / western larch SRC | 0.500 | 49.6 | 58.2 | 33.1 | 3.3 | 0.356–0.102 | 5 |

[a]SML, submerchantable logs; ST, small trees; SRC, sawmill residue chips.
[b]OD, ovendry.
[c]Refining passes are in addition to a single fiberization pass.

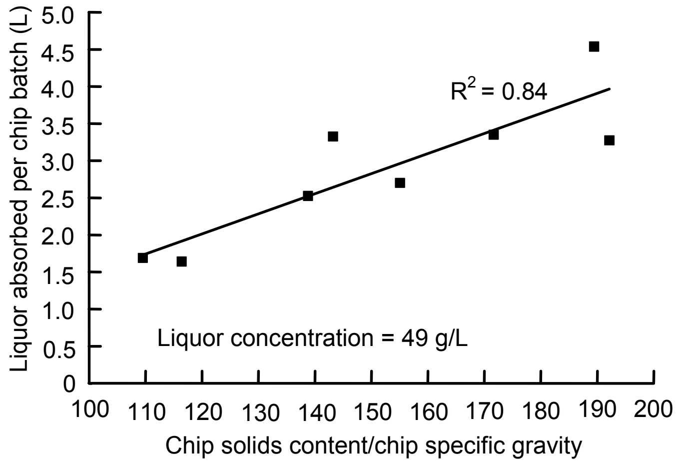


**Figure 1—Correlation between amount of liquor absorbed and the chip solids content/chip specific gravity ratio, using a constant liquor concentration.**

operating conditions were identical or very similar for all raw materials to reduce variables as we looked for differences between raw materials. Table 1 shows considerable variation in the percentage of sodium sulfite absorbed when the liquor concentration was held constant. For the constant liquor concentration, the correlation between sulfonate content and sodium sulfite absorption is very weak ($R^2 = 0.20$), and that between pulp sulfonate content and wood specific gravity is equally weak ($R^2 = 0.22$). Correlation between liquor absorbed and chip solids content was strong ($R^2 = 0.73$) when liquor concentration was constant. However, as shown in Figure 1, there was a stronger correlation ($R^2 = 0.84$) between the amount of liquor absorbed and chip solids content/chip specific gravity for constant liquor concentration. Prior to the 20-min steaming segment of the impregnation sequence, there was considerable variation in chip solids content between raw materials. Chip solids content was not measured again after steaming but apparently the differences remained, which affected liquor absorption. Because liquor uptake was highly dependent on chip solids content and specific gravity (constant liquor concentration), the experiment was repeated with liquor concentration (grams per liter) varied in an attempt to achieve a more consistent treatment with approximately the same amount of sodium sulfite absorbed by the different wood species (variable liquor concentration). Consequently, the amount of sodium sulfite absorbed in the variable liquor concentration trial was more consistent, with the SRC samples absorbing more and the other raw materials absorbing less liquor than in the original trial. Western larch ST was not included in the repeat trial because of sample depletion. The impregnation, fiberization, and refining conditions selected and used in both trials might not be optimum for all the raw materials.

An Andritz Sprout-Bauer (Quincy, Pennsylvania) model 12-1CP 305-mm-diameter pressurized refiner, fitted with plate pattern D2B505, was used for fiberization. All impregnated raw materials were steamed for 10 min at 206.8 kPa before fiberization. To minimize the experimental variables, identical fiberization procedures were followed for all raw material replicates. Fiberized pulp was wet screened through a 0.2-mm-slot flat screen. Screen accepts and rejects were refined separately in a Sprout-Waldron model 105-A 305-mm-diameter atmospheric refiner, also fitted with plate pattern D2B505. A constant volume of shredded pulp was delivered to the refiner inlet by a constant-speed belt conveyor, and dilution water was added to the shredded pulp to adjust refiner consistency to approximately 20%. Multiple passes were necessary to reduce pulp Canadian Standard Freeness (CSF) to approximately 200 mL, when accepts and rejects were combined. An additional pass was run on the combined pulp to reduce CSF to less than 100 mL. Number of refining passes and range of refiner plate gap settings for all raw materials are presented in Table 1. Energy consumed during fiberization and refining was measured using an Ohio Semitronic (Hilliard, Ohio) model WH30-11195 integrating watt-hour meter attached to the power supply of the 44.8-kW electric motors, measuring amperes, volts, and power factor. Energy consumption values for fiberizing and refining were reported as watt-hours per kilogram (ovendry weight basis), with the idling energy subtracted. Latency was removed from the pulp after fiberization and each refining step by soaking the pulp in 90°C water for a minimum of 30 min, with occasional stirring. A minimum of four replicates for each treatment level was prepared for each of the eight raw materials. Pulp yield was not determined.

## Pulp Testing, Handsheet Formation, and Testing

The CSF was measured according to TAPPI Test Method T227. Shive contents were determined with a Pulmac shive analyzer (Pulmac Instruments International, Montpelier, Vermont), using a disk with 0.10-mm slot openings. Average fiber length, fines content, and fiber coarseness were determined using a Kajaani (Norcross, Georgia) FS-100 analyzer. Pulp sulfonate contents were determined according to a procedure described by Katz and others (1984). Handsheets weighing 60 g/m$^2$ were made according to TAPPI Test Method T205. Burst and tear indexes were measured according to TAPPI Test Methods T403 and T414, respectively. Tensile breaking properties and paper smoothness were measured according to TAPPI Test Methods T494 and T538, respectively. Brightness, printing opacity, and light-scattering coefficient were measured with a Technidyne Corporation (New Albany, Indiana) Technibrite Model TB-1 diffuse brightness apparatus according to TAPPI Test Method T525.

## Statistics

Each CTMP was processed to CSF levels greater and less than the 100-mL target. A set of 10 handsheets were made and tested for each pulp. The individual test results were used to perform a Dunnett's multiple comparison procedure, which provided statistical significance at a 95% confidence interval. Mean, standard deviation, and coefficient of variation were computed for each property tested in a handsheet set. Mean values from the four replicates were combined and averaged to provide values greater and less than 100 CSF, which were interpolated to estimate a value for 100 CSF.

# Results and Discussion

## Presentation of Results

Instead of presenting data for all CTMP evaluations, the interpolated values for 100-mL CSF are presented in Tables 2 and 3 for the eight raw materials. A careful examination of the tables reveals that properties responded differently within a raw material classification to a change in sodium sulfite content.

Comparisons between raw materials were accomplished by computing a percentage change from the controls (SRC) (Figs. 2, 3, 4, and 5). The SML and ST were considered an alternative raw material, and we were interested in how they compared with a traditional raw material (SRC). The Douglas-fir/western larch SRC was the control raw material for comparison with Douglas-fir and western larch raw materials, and the lodgepole pine SRC was used for comparison with lodgepole pine raw materials. Results of the statistical analysis were added to Figures 2, 3, 4, and 5. The S indicates that a specific property was significantly different from the SRC, as determined by the Dunnett's multiple comparison procedure. In Figures 2, 3, 4, and 5, the SRC values (Tables 1and 2) are different between the constant liquor concentration and the variable liquor concentration, which affected the percentage change calculations.

Figures 6, 7, 8, and 9 show the percentage difference between TMPs previously reported (Barbour and Skog 1997, Myers and others 1999a) and CTMPs evaluated for this study, using the same raw materials. Statistical analysis was not performed on the comparison between TMP and CTMP.

## Pulp Preparation and Properties

Energy consumption is traditionally high in preparing mechanical pulp; therefore, any new raw material that consumes less energy is desirable, and this did occur with western larch SML and ST. Energy consumption was greater for the lodgepole pine SML and ST and the Douglas-fir SML and ST (Fig. 2), and several of these increases were statistically significant compared with their respective controls. Pulmac shive decreased when liquor concentration was held constant for lodgepole pine SML, western larch SML, and western larch ST; it increased for Douglas-fir SML and ST and significantly increased for the lodgepole pine ST (Fig. 2). Pulmac shive decreased when liquor concentration varied for Douglas-fir SML and western larch SML but increased for lodgepole pine SML and ST and Douglas-fir ST. When liquor concentration was constant, fiber length decreased for all raw materials except the Douglas-fir ST (Fig. 3), with statistically significant decreases for lodgepole pine SML and western larch ST. All fiber length decreases were significant when liquor concentration was varied. Decreased fines content is desirable especially if the fines were the result of fiber shortening, and this occurred in this study with four raw materials (Fig. 3) when liquor concentration was constant, with the decreases for lodgepole pine and Douglas-fir ST statistically significant. Western larch SML and ST under constant liquor concentration had significantly increased fines content. Fines content increased for all materials when liquor concentration was varied, with the increases for Douglas-fir SML and ST and western larch SMC statistically significant. Coarseness decreased for all raw materials when liquor concentration was held constant, significantly for Douglas-fir SML and ST and western larch SML. Because most western softwood species are rather coarse fibered, this coarseness reduction might be desirable. Unfortunately, when liquor concentration was varied, all materials except Douglas-fir ST exhibited greater fiber coarseness, with none statistically significant.

The western larch SML and ST might have been severely damaged during CTMP preparation under constant liquor concentration because the shive content, fiber length, and coarseness all decreased and the fines content increased significantly. The fibers were apparently being shortened and decreased in diameter. Lodgepole pine SML might also have been damaged.

When the sodium sulfite treatment was decreased within a raw material group, fibers were cut into shorter lengths (decreasing fiber length and increasing fines content) without removing as much of the cell wall (higher coarseness). These changes in fiber configuration could impact paper strength properties.

For the majority of raw materials evaluated in this study, more energy was consumed in producing a CTMP than for a TMP at the same freeness (Leask 1987) (Fig. 6). However, the CTMP appears to yield a higher quality fiber than obtained with TMP (Fig. 7). Shive content was lower, average fiber length was longer, fines content was lower, and fiber coarseness was higher for the majority of raw materials. These values imply that a higher quality fiber was obtained with the CTMP process.

## Strength Properties

Except for western larch ST and lodgepole pine ST, the other four raw materials had higher apparent paper density than did their corresponding SRC (Table 3) in the constant liquor concentration trial. These apparent density differences are statistically significant, except for western larch SML

**Table 2—Pulp properties interpolated to 100 Canadian Standard Freeness**

| Input material[a] | Total energy (W·h/OD[b] kg) | Pulmac shive <0.004 mm (%) | Kajaani FS-100 analysis, Length-weighted: Average (mm) | Kajaani FS-100 analysis, Length-weighted: Fines (%) | Kajaani FS-100 analysis: Coarseness (mg/m) | Sulfonate content (mmole/kg) |
|---|---|---|---|---|---|---|
| **Constant liquor concentration** | | | | | | |
| Lodgepole pine SML, impregnated with 7.7% $Na_2SO_3$ | 4,310 | 0.13 | 1.21 | 4.01 | 0.27 | 81.7 |
| Lodgepole pine ST, impregnated with 5.2% $Na_2SO_3$ | 4,794 | 0.47 | 1.28 | 3.21 | 0.33 | 70.8 |
| Lodgepole pine SRC, impregnated with 3.2% $Na_2SO_3$ | 4,087 | 0.21 | 1.43 | 4.34 | 0.35 | 57.6 |
| Douglas-fir SML, impregnated with 5.4% $Na_2SO_3$ | 5,469 | 0.33 | 1.28 | 3.61 | 0.32 | 64.7 |
| Douglas-fir ST, impregnated with 4.7% $Na_2SO_3$ | 6,939 | 0.67 | 1.50 | 2.95 | 0.34 | 79.5 |
| Western larch SML, impregnated with 5.2% $Na_2SO_3$ | 3,627 | 0.23 | 1.28 | 4.70 | 0.34 | 103.4 |
| Western larch ST, impregnated with 4.0% $Na_2SO_3$ | 3,633 | 0.18 | 1.18 | 4.84 | 0.37 | 62.7 |
| Douglas-fir / western larch SRC, impregnated with 2.6% $Na_2SO_3$ | 4,227 | 0.31 | 1.37 | 3.81 | 0.41 | 70.1 |
| **Variable liquor concentration** | | | | | | |
| Lodgepole pine SML, impregnated with 3.7% $Na_2SO_3$ | 6,217 | 0.24 | 1.09 | 5.37 | 0.44 | 54.0 |
| Lodgepole pine ST, impregnated with 2.8% $Na_2SO_3$ | 5,684 | 0.21 | 1.14 | 4.84 | 0.34 | 59.3 |
| Lodgepole pine SRC, impregnated with 3.8% $Na_2SO_3$ | 4,698 | 0.20 | 1.31 | 4.80 | 0.30 | 69.6 |
| Douglas-fir SML, impregnated with 3.0% $Na_2SO_3$ | 5,848 | 0.23 | 1.12 | 5.45 | 0.39 | 50.5 |
| Douglas-fir ST, impregnated with 3.6% $Na_2SO_3$ | 4,558 | 0.31 | 1.26 | 4.07 | 0.34 | 66.8 |
| Western larch SML, impregnated with 3.4% $Na_2SO_3$ | 3,957 | 0.18 | 1.23 | 4.96 | 0.40 | 57.5 |
| Douglas-fir / western larch SRC, impregnated with 3.3% $Na_2SO_3$ | 4,195 | 0.28 | 1.60 | 3.26 | 0.36 | 76.5 |

[a]SML, submerchantable logs; ST, small trees; SRC, sawmill residue chips.
[b]OD, ovendry.

**Table 3—Paper properties interpolated to 100 Canadian Standard Freeness**

| Input material[a] | Apparent density ($kg/m^3$) | Burst index ($kPa·m^2/g$) | Tear index ($mN·m^2/g$) | Tensile index (N·m/g) | Stretch (%) | TEA[b] ($J/m^2$) | Smoothness (SU[c]) | ISO brightness (%) | Printing opacity (%) | Scattering coefficient ($m^2/kg$) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Constant liquor concentration** | | | | | | | | | | |
| Lodgepole pine SML, impregnated with 7.7% $Na_2SO_3$ | 543 | 2.03 | 4.67 | 43.4 | 1.81 | 35.86 | 125 | 38.9 | 97.0 | 36.6 |
| Lodgepole pine ST, impregnated with 5.2% $Na_2SO_3$ | 456 | 2.06 | 4.83 | 43.9 | 2.08 | 41.33 | 157 | 43.7 | 97.6 | 43.7 |
| Lodgepole pine SRC, impregnated with 3.2% $Na_2SO_3$ | 505 | 1.94 | 5.21 | 40.3 | 1.99 | 37.00 | 133 | 42.4 | 98.0 | 43.9 |
| Douglas-fir SML, impregnated with 5.4% $Na_2SO_3$ | 534 | 2.10 | 4.87 | 42.1 | 2.09 | 41.53 | 116 | 24.0 | 99.5 | 34.1 |
| Douglas-fir ST, impregnated with 4.7% $Na_2SO_3$ | 535 | 2.35 | 5.66 | 45.3 | 2.17 | 45.48 | 115 | 22.6 | 99.6 | 31.0 |
| Western larch SML, impregnated with 5.2% $Na_2SO_3$ | 474 | 1.44 | 4.27 | 34.5 | 1.61 | 24.97 | 161 | 31.2 | 99.0 | 35.6 |
| Western larch ST, impregnated with 4.0% $Na_2SO_3$ | 458 | 1.26 | 3.64 | 29.2 | 1.55 | 20.26 | 205 | 30.1 | 99.1 | 36.4 |
| Douglas-fir / western larch SRC, impregnated with 2.6% $Na_2SO_3$ | 469 | 1.85 | 5.21 | 39.2 | 1.94 | 33.68 | 158 | 27.9 | 99.4 | 37.9 |
| **Variable liquor concentration** | | | | | | | | | | |
| Lodgepole pine SML, impregnated with 3.7% $Na_2SO_3$ | 552 | 2.15 | 4.24 | 44.8 | 2.01 | 43.03 | 98 | 41.2 | 97.2 | 41.4 |
| Lodgepole pine ST, impregnated with 2.8% $Na_2SO_3$ | 639 | 2.53 | 4.03 | 49.0 | 2.33 | 52.18 | 61 | 39.8 | 97.1 | 39.0 |
| Lodgepole pine SRC, impregnated with 3.8% $Na_2SO_3$ | 556 | 2.25 | 4.52 | 43.5 | 2.37 | 46.40 | 124 | 42.4 | 96.6 | 39.8 |
| Douglas-fir SML, impregnated with 3.0% $Na_2SO_3$ | 532 | 2.31 | 5.06 | 45.0 | 2.19 | 45.55 | 103 | 27.2 | 99.6 | 39.9 |
| Douglas-fir ST, impregnated with 3.6% $Na_2SO_3$ | 537 | 2.06 | 4.76 | 42.7 | 2.22 | 43.80 | 129 | 26.3 | 99.4 | 36.5 |
| Western larch SML, impregnated with 3.4% $Na_2SO_3$ | 490 | 1.47 | 3.93 | 33.1 | 1.61 | 24.33 | 167 | 32.2 | 98.9 | 38.1 |
| Douglas-fir / western larch SRC, impregnated with 3.3% $Na_2SO_3$ | 496 | 2.08 | 5.65 | 39.8 | 2.14 | 39.59 | 155 | 28.8 | 99.3 | 37.2 |

[a]SML, submerchantable logs; ST, small trees; SRC, sawmill residue chips.
[b]TEA, tensile energy absorption.
[c]SU, smoothness units.

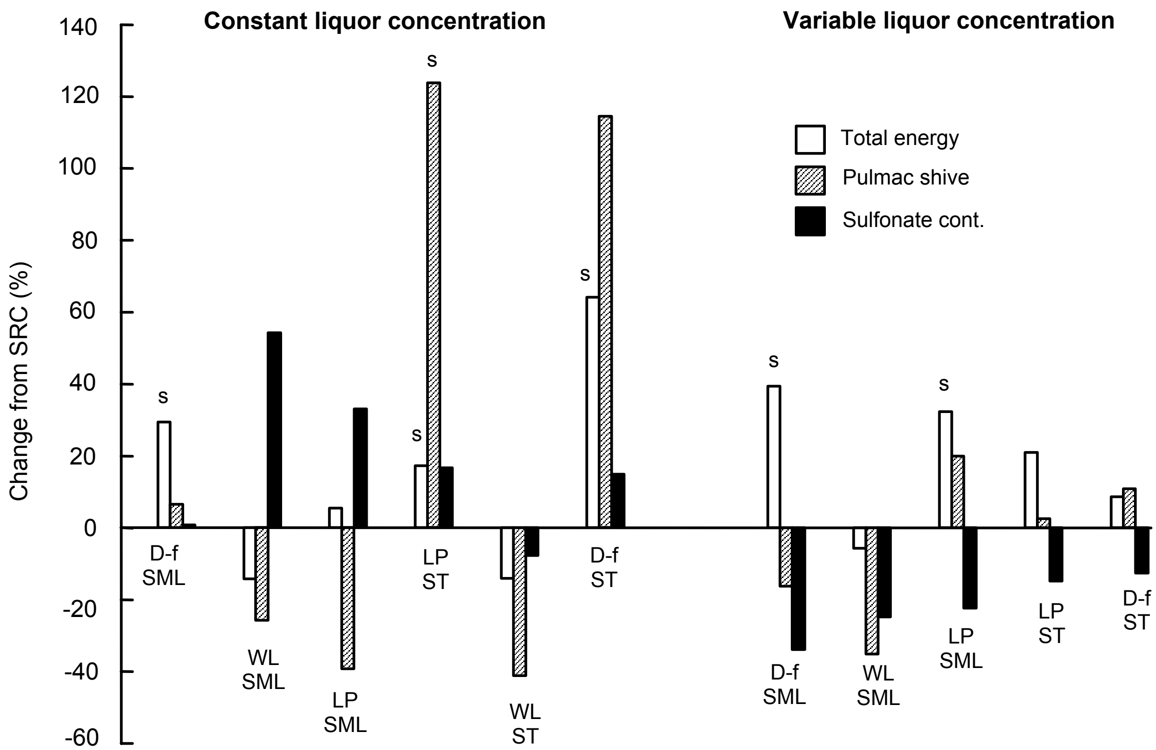


**Figure 2—Differences between several small-diameter tree resources and sawmill residue chips (SRC) with liquor concentration constant and varied (S, statistical significance; D-f, Douglas-fir; WL, western larch; LP, lodgepole pine; SML, submerchantable log; ST, small tree).**

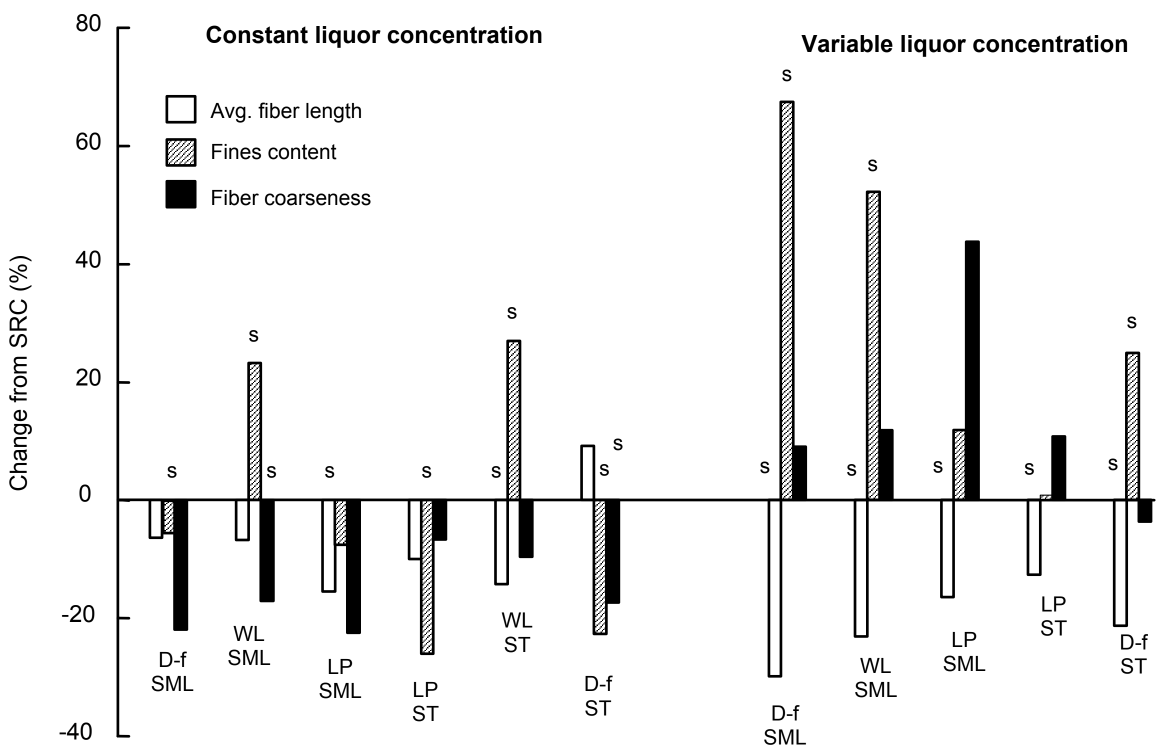


**Figure 3—Differences between several small-diameter tree resources and sawmill residue chips (SRC) with liquor concentration constant and varied (S, statistical significance; D-f, Douglas-fir; WL, western larch; LP, lodgepole pine; SML, submerchantable log; ST, small tree).**

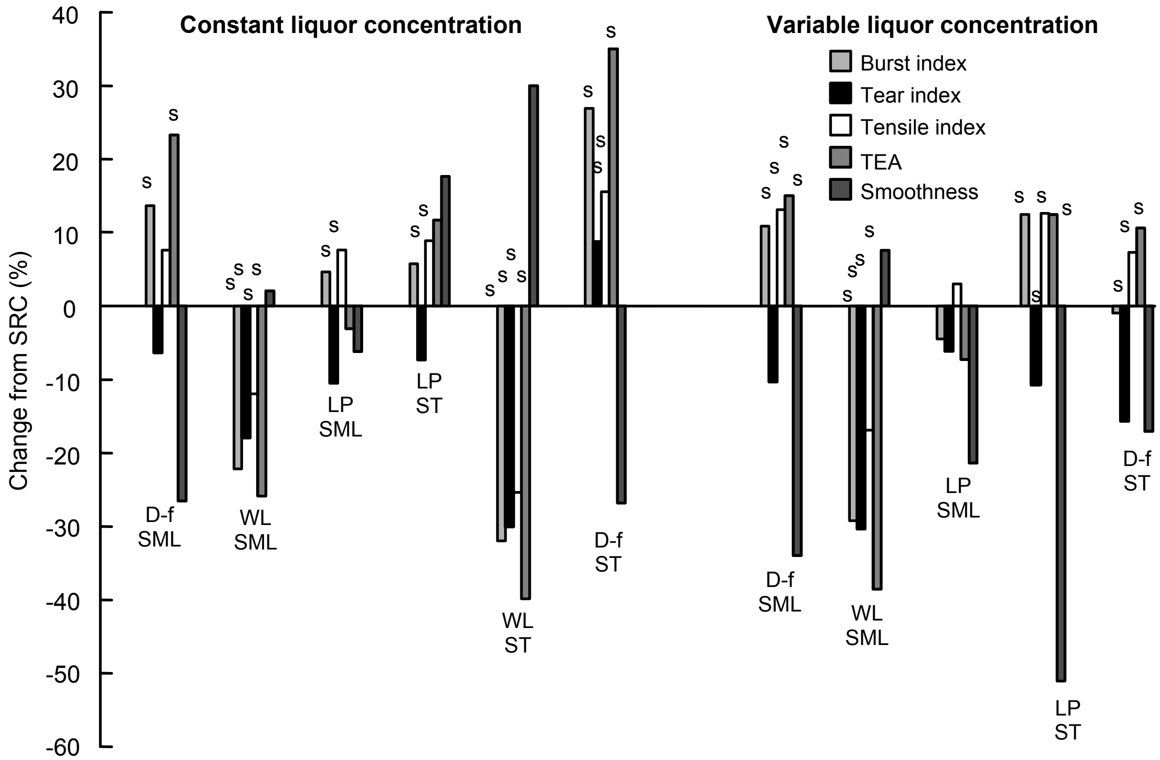


**Figure 4—Differences between several small-diameter tree resources and sawmill residue chips (SRC) with liquor concentration constant and varied (S, statistical significance; D-f, Douglas-fir; WL, western larch; LP, lodgepole pine; SML, submerchantable log; ST, small tree; TEA, tensile energy absorption).**

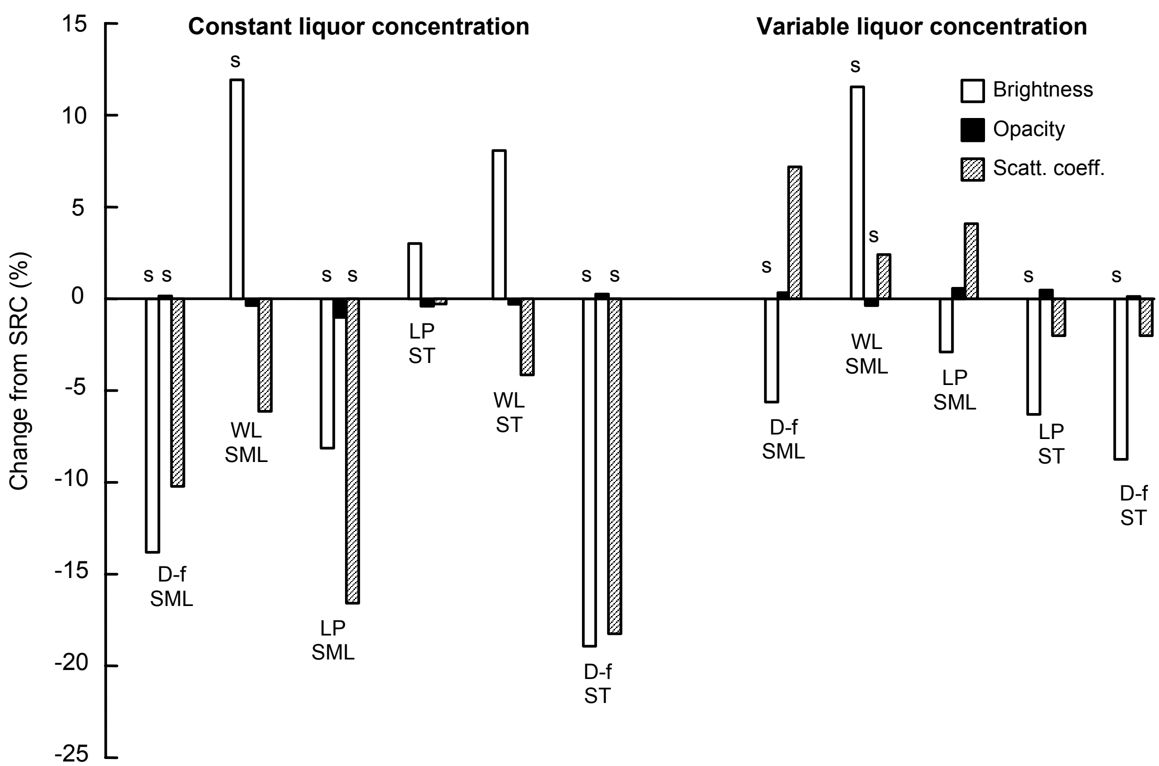


**Figure 5—Differences between several small-diameter tree resources and sawmill residue chips (SRC) with liquor concentration constant and varied (S, statistical significance; D-f, Douglas-fir; WL, western larch; LP, lodgepole pine; SML, submerchantable log; ST, small tree).**

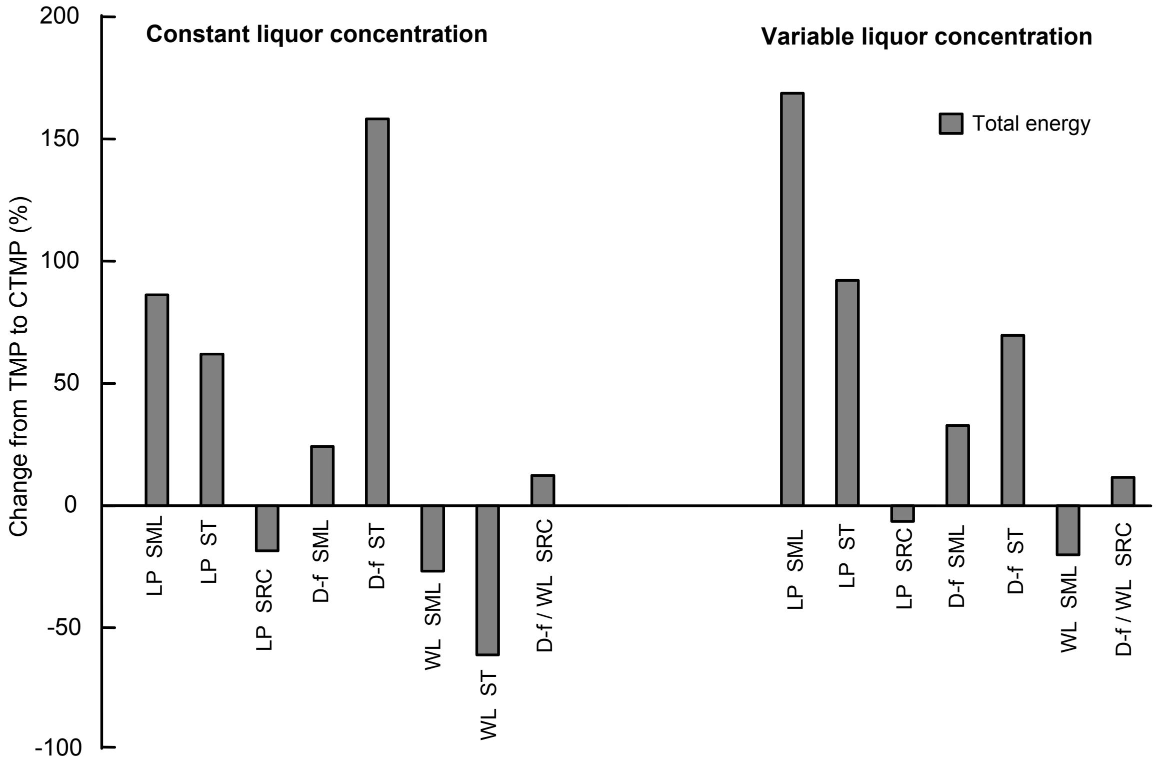


**Figure 6—Difference between chemithermomechanical pulp (CTMP) and thermomechanical pulp (TMP) using constant and variable liquor concentration (D-f, Douglas-fir; WL, western larch; D-f/WL, mixture of Douglas-fir and western larch; LP, lodgepole pine; SRC, sawmill residue chips; SML, submerchantable log; ST, small tree).**

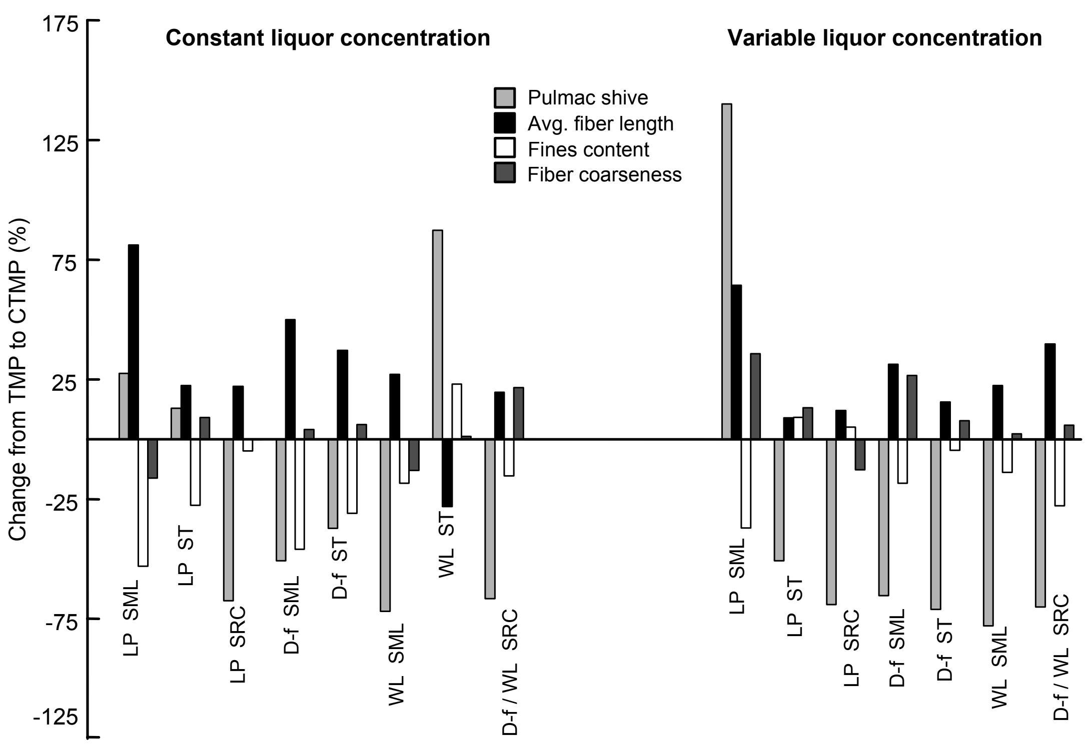


**Figure 7—Difference between chemithermomechanical pulp (CTMP) and thermomechanical pulp (TMP) using constant and variable liquor concentration (D-f, Douglas-fir; WL, western larch; D-f/WL, mixture of Douglas-fir and western larch; LP, lodgepole pine; SRC, sawmill residue chips; SML, submerchantable log; ST, small tree).**

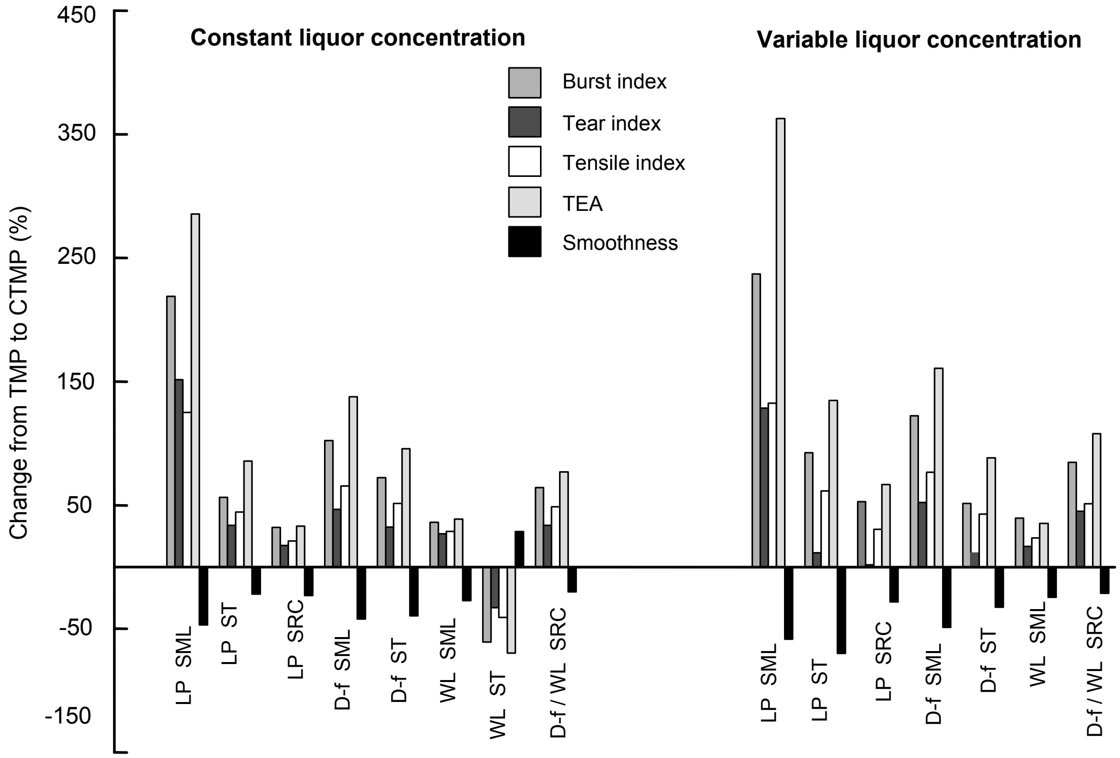


**Figure 8—Difference between chemithermomechanical pulp (CTMP) and thermomechanical pulp (TMP) using constant and variable liquor concentration (D-f, Douglas-fir; WL, western larch; D-f/WL, mixture of Douglas-fir and western larch; LP, lodgepole pine; SRC, sawmill residue chips; SML, submerchantable log; ST, small tree; TEA, tensile energy absorption).**

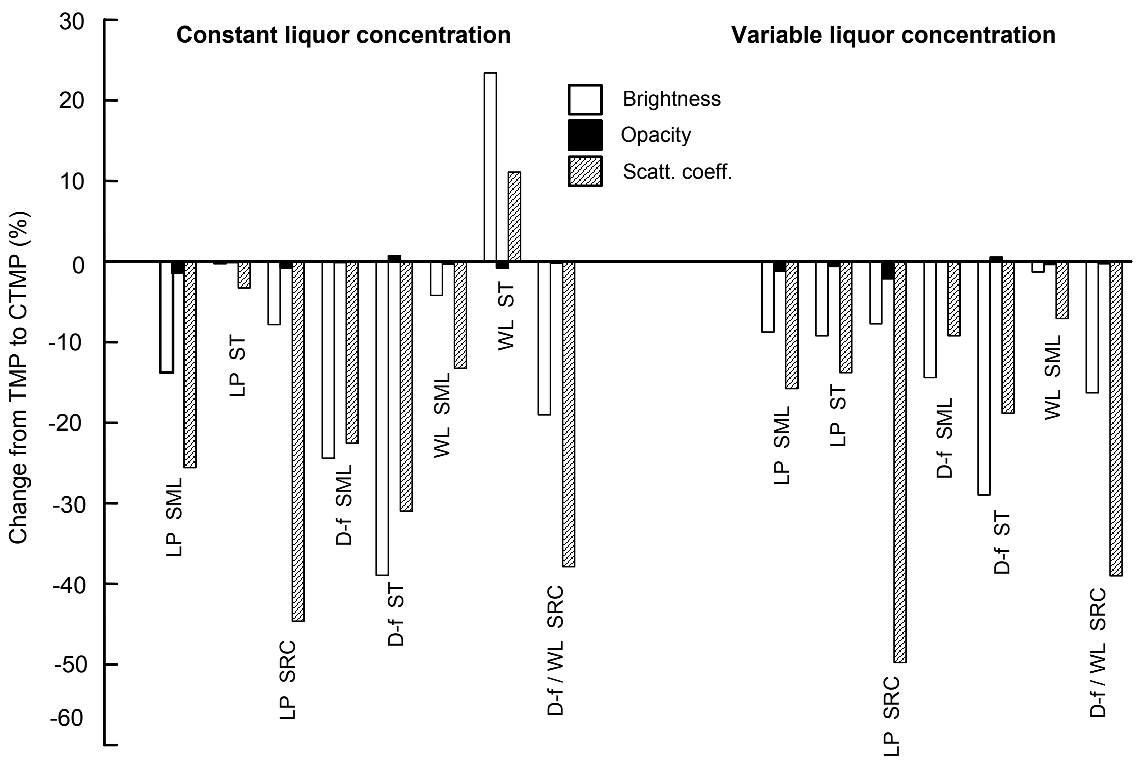


**Figure 9—Difference between chemithermomechanical pulp (CTMP) and thermomechanical pulp (TMP) using constant and variable liquor concentration (D-f, Douglas-fir; WL, western larch; D-f/WL, mixture of Douglas-fir and western larch; LP, lodgepole pine; SRC, sawmill residue chips; SML, submerchantable log; ST, small tree).**

and ST. Lodgepole pine SML and western larch SML were the only two materials that had apparent densities lower than their corresponding SRC in the variable liquor concentration trial. The apparent density increases of lodgepole pine ST and Douglas-fir SML and ST were statistically significant. Most handsheet strength properties, except tear index, are density dependent and might be affected.

Lodgepole pine ST and western larch ST, both prepared with constant liquor concentration, were the only two raw materials with a lower density than found with TMP. The other CTMPs had higher density than the TMPs, which probably reflects better consolidation and bonding obtained with the higher quality CTMP fiber.

When liquor concentration was held constant, all strength properties increased for Douglas-fir ST and all decreased for western larch SML and ST (Fig. 4). With one exception (smoothness), all these changes were statistically significant. Tear index decreased and all other strength properties increased for lodgepole pine ST and Douglas-fir SML. Lodgepole pine SML had burst index and tensile index increases and tear index and TEA decreases. A smoother paper surface, as indicated by a smoothness decrease, is desirable and did occur with the lodgepole pine SML and Douglas-fir SML and ST.

Several changes occurred in strength properties when the sodium sulfite concentration was reduced (variable liquor concentration). The percentage change from SRC was different for each strength property. Lodgepole pine SML and Douglas-fir ST were impacted more severely by the reduced sodium sulfite treatment than were the other raw materials.

Compared with its corresponding TMP, western larch ST (constant liquor concentration) was the only material to have all negative paper strength properties (Fig. 8). All the other CTMPs had better properties than their corresponding TMPs, probably the result of better fiber quality.

Strength properties were examined in several ways because we were searching for possible correlations with the different parameters. Tables 2 and 3 show that within a raw material group, reducing the sodium sulfite treatment generally increased energy consumption, increased apparent density, and improved most of the strength properties (a lower smoothness unit number is better than a higher number). For all raw materials, when each strength property was compared against its respective sulfonate number, the $R^2$ numbers indicated that very weak to no correlations existed. Correlation between energy consumption and shive content was weak ($R^2$ = 0.24) and was essentially nothing for correlation between energy consumption and average fiber length ($R^2$ = 0.02), fines content ($R^2$ = 0.002), and coarseness ($R^2$ = 0.007). Strength properties, with the exception of tear index, had moderate ($R^2$ = 0.55 to 0.62) correlations with energy consumption and moderate to strong ($R^2$ = 0.54 to 0.80) correlations with apparent density. Tear index is very dependent upon fiber length and had a moderate ($R^2$ = 0.61) correlation with energy consumption. Fiber changes of decreased fiber length, more fines, and higher coarseness were initially thought to reduce bonding and negatively affect properties but were apparently beneficial in this study.

Potential correlations between wood specific gravity, energy consumption, pulp properties, and paper strength were also examined. All correlations ranged from moderate ($R^2 \leq 0.5$) to very weak, which might be anticipated since wood specific gravity is a macrodetermination. Paper is made from individual wood fibers, which is wood separated to a microscale (individual fibers). Pulp sulfonate content increased as wood specific gravity increased, probably because the higher specific gravity was indicative of more woody material to absorb the sodium sulphite. Energy consumption declined as wood specific gravity increased, which might indicate brittle fracture or the presence of more fracture zones within the cell walls. Fiber length and fines content remained essentially constant as wood specific gravity increased. Fiber coarseness increased as wood specific gravity increased, probably due to the presence of thicker fiber walls. Paper density decreased as wood specific gravity increased, probably caused by poorer bonding between the increasingly coarser fibers, which should affect the density dependent paper properties. Tensile index, which is density dependent, decreased as wood specific gravity increased. Tear index, which is fiber length dependent, did not change as wood specific gravity increased. The paper surface became rougher as wood specific gravity increased, due to the increasing amount of coarser fibers.

## Optical Properties

High opacity and light scattering properties are desirable for mechanical pulps, which are heavily used to produce various printing and writing papers. Three of the small-diameter resources had greater brightness when pulped with CTMP than did their corresponding SRC, at a higher sodium sulfite treatment (constant liquor concentration), but this dropped to only one raw material having greater brightness at the lower sodium sulfite treatment (variable liquor concentration) (Fig. 5). The actual printing opacity values (Table 3) were very high for all small-diameter resources, and the percentage change from their corresponding SRC was small at all sodium sulfite treatment levels. Scattering coefficient, which is affected by fiber properties and bonding, had some large and significant decreases for all the small-diameter resources at the higher sodium sulfite treatment level (constant liquor concentration) (Fig. 5). Decreasing the sodium sulfite treatment level (variable liquor concentration) increased the light scattering coefficients of the three SML materials and caused less of a decrease for the two ST materials (Fig. 5). Scattering coefficient decreased as wood specific gravity increased, probably the result of increased fiber coarseness, less fines, and no change in fiber length. Less material was available to scatter light.

Brightness is usually higher with CTMP than with TMP, but in this study, that only occurred with western larch ST (constant liquor concentration). All of the other CTMPs had lower brightness than their corresponding TMPs (Fig. 9). A probable cause of the lower CTMP brightness was mold growing on the chips, which were older than chips used to prepare TMP. A reduced scattering coefficient was expected and did occur with CTMP (Leask 1987), probably a reflection of higher fiber quality and better bonding. The lower scattering coefficient also decreased opacity for the majority of CTMP.

# Conclusions

Results from this study indicate that Douglas-fir SML and ST and lodgepole pine ST are acceptable raw materials for CTMP. The dark color and low brightness of the Douglas-fir pulps might make them unacceptable. Lodgepole pine SML is marginal and might become acceptable through process optimization. Western larch SML and ST do not appear to be acceptable raw materials for CTMP. For a majority of these materials, CTMP improved the properties of the final product compared with the corresponding TMPs. Therefore, using CTMP should improve the quality of pulp from some small-diameter material, thus making it more valuable and helping to achieve overall forest management objectives.

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