PACKAGING GRADE KRAFT PULP FROM SMALL-DIAMETER SOFTWOOD

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ABSTRACT

Many forests in the interior western region of the United States consist of densely stocked small-diameter trees of mixed softwood species. These forests have a potential for large-scale insect infestations, disease, and fire. Active management of these forests is costly and will probably generate a large volume of materials with very little commercial value. Using these materials to produce certain grades of paper might bring economic and environmental benefits. The principal wood species found in these forests are western larch, Douglas-fir, and lodgepole pine. The objective of this study was to establish the suitability of kraft pulping of interior western small-diameter matured softwoods for production of packaging grades of paper from high kappa number pulps. The kraft pulping process, suitable for all wood species, was used in the preparation of packaging grade handsheets. Pulps were prepared at around 70 kappa using the same liquor concentration and liquor to wood ratio but cooking to various H-factors. The pulp yield varied significantly even at similar kappa numbers for the various wood species. Mechanical properties of handsheets differed significantly for different raw materials when compared at similar CSF and sheet density levels. Adhesion-based properties, such as tensile strength and burst index values were highest for lodgepole pine and lowest for western larch and Douglas-fir/western larch mixture. However, tear values were highest for western larch and lowest for lodgepole pine. The vacuum compression apparatus (VCA) compression test was also performed to evaluate the suitability of the pulps for packaging grade paper.

INTRODUCTION

The competing uses of forestlands, the environmental impact of forest operations, and sustainable forest management practices have negative impacts on the supply of suitable fiber to the pulp and paper industries. The technical limitation and cost effectiveness of recycled paper for certain grades of paper and paperboard prohibit the use of recycled paper beyond certain limits. Wood fiber supply in the United States could be increased by using industrial wood waste (1) and small-diameter trees of little or no commercial value (2).

Forests in the interior western region consist of densely stocked small-diameter trees of mixed softwood species. The stands are mature and will likely never reach log diameter of commercial importance. These trees contain a larger proportion of compression wood (3). Compression wood has a greater density and slightly more extractives than regular wood. Compression wood tracheids are shorter with thicker cell walls having 30% to 40% more lignin and 20% to 25% less cellulose (3). Pulp and paper products from compression wood are inferior to those of normal pulpwood. Chemical pulping of compression wood gives lower yield of pulp containing stiffer fibers with a high lignin content compared with that of normal wood (3). Handsheets prepared from compression wood chemical pulp are inferior to those obtained from normal wood. Compression wood fibers are not suitable for mechanical pulping due to their short length, thick walls, and high lignin content. Such fibers may be used in packaging grades.

Forests growing on the eastern side of the Pacific Northwest Cascade Mountains consist of densely stocked, small-diameter trees that have large potential for large-scale insect infestations, disease, and fire. Active management of these forests is costly and will probably generate large volumes of materials with very little commercial value. Using these materials to produce certain grades of paper might bring economic and environmental benefit. Kraft pulps, covering a wide range of kappa number and yield, were prepared from interior

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Western small-diameter trees at the University of Washington (2). There were essentially no differences between the small-diameter raw materials when pulps were prepared at low kappa number. The objective of this study was to establish the suitability of Kraft pulping of interior Western small-diameter matured softwoods for production of packaging grades of paper from high kappa number pulps.

EXPERIMENTAL

Raw Materials

All raw materials used in this study were procured from the Colville National Forest (eastern Washington) or the Idaho Panhandle National Forest (western Idaho). The selected species were Douglas-fir, lodgepole pine, and western larch. Douglas-fir/western larch mixture and lodgepole pine sawmill residue chips (SRC) were obtained from Vaagen Bros. Lumber (Colville, WA). The sawmill residue chips (SRC) were screened to accept the chips between 2 and 10 mm thick. The submerchantable logs (SML) had a <89-mm end diameter and were the top logs cut from the trees. The small-diameter trees (ST) had a <127-mm diameter at breast height and were the entire tree. All logs were debarked manually and chipped to 19 mm long in a four-knife commercial-sized chipper. Chipped logs and SRC were screened to remove all chips >38 and <6 mm long. Screened chips were thoroughly mixed in a large V-mixer. The green chips were divided into 4- to 5-kg sample sizes, placed in polyethylene bags, and stored at 4°C until pulped. Raw materials used in our cooking were western larch submerchantable logs (WL-SML), Douglas-fir/larch saw mill residue chips (DF/WL-SRC), Douglas-fir small-diameter trees (DF-ST), Douglas-fir submerchantable logs (DF-SML), lodgepole pine saw mill residue chips (LP-SRC), lodgepole pine submerchantable logs (LP-SML), and lodgepole pine small trees (LP-ST).

Kraft Pulping

The pulping experiments were carried out in a 23-L stainless steel batch digester. The digester is stationary with pumped liquor circulation of around 17 L/min. White liquor of 20% active alkalinity and 25% sulfidity were prepared using industrial grade sodium hydroxide and sodium sulfide. Two kilograms of wood chips on oven-dry (o.d.) basis were used in each cook. For yield measurement, a screen basket that allows free circulation of cooking liquor was filled with about 100 g of o.d. chips and put in the middle of the digester within the chips. After putting the chips in the digester, a vacuum of about negative 82 kPa was created in the digester and held for at least five min before adding the white liquor into the digester. This will create better penetration of white liquor into the chips. The liquor to chips ratio of 6:1 was maintained during cooking. After initial circulation of white liquor for a few minutes, heating of circulating liquor began by indirect heating with steam. The temperature of the digester liquor was raised to 80°C within 10 to 15 min. The temperature was then raised to cooking temperature of 170°C in 60 min. The condensate line was left open to avoid any condensate buildup in the steam line. The cooking time was adjusted by trial and error to obtain a pulp of kappa number 70. The desired ramp time, cooking time, and temperature were maintained by using an automatic system. The cooking conditions, pulp yield, and kappa number are presented in Table I.

<table>
<thead>
<tr>
<th>Wood sample</th>
<th>Active alkalinity (%)</th>
<th>Sulfidity (%)</th>
<th>Cooking time (min)</th>
<th>Cooking temperature (°C)</th>
<th>Pulp yield (%)</th>
<th>Pulp kappa number</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL-SML</td>
<td>20</td>
<td>25</td>
<td>65</td>
<td>170</td>
<td>49.9</td>
<td>71</td>
</tr>
<tr>
<td>LP-SML</td>
<td>20</td>
<td>25</td>
<td>55</td>
<td>170</td>
<td>53.1</td>
<td>71</td>
</tr>
<tr>
<td>DF-ST</td>
<td>20</td>
<td>25</td>
<td>80</td>
<td>170</td>
<td>53.9</td>
<td>68.5</td>
</tr>
<tr>
<td>DF-SML</td>
<td>20</td>
<td>25</td>
<td>72</td>
<td>170</td>
<td>51</td>
<td>70</td>
</tr>
<tr>
<td>LP-SRC</td>
<td>20</td>
<td>25</td>
<td>68</td>
<td>170</td>
<td>50.7</td>
<td>72</td>
</tr>
<tr>
<td>LP-ST</td>
<td>20</td>
<td>25</td>
<td>65</td>
<td>170</td>
<td>53.4</td>
<td>71.6</td>
</tr>
<tr>
<td>DF/WL-SRC</td>
<td>20</td>
<td>25</td>
<td>67</td>
<td>170</td>
<td>51.6</td>
<td>69.6</td>
</tr>
</tbody>
</table>

After cooking, the black liquor was discharged through a vent at the bottom of the digester. Circulating hot water was then used to wash the cooked chips in the digester. After through washing, the chips were removed from the
digester and disintegrated in a refiner at around 5% consistency. The pulp was then dewatered using a vacuum system, disintegrated, and stored in a cold room for further processing. For yield measurement, the cooked chips in the screen bucket were disintegrated and washed well on a filter paper. The pulp was then dried in an oven at 104°C for about 24 h. The ratio of o.d. pulp and initial o.d. chips multiplied by 100 gives the yield of the pulp.

**Pulp Testing**

The kraft pulps were beaten in a PFI mill at three levels varying from 4,000 to 15,000 revolutions to obtain three levels of Canadian Standard Freeness (CSF). The CSF was measured according to TAPPI Test Method T227. Average fiber length, fines content, and fiber coarseness were determined using a Kajaani FS-100 analyzer. Handsheets weighing 205 g/m² were made according to TAPPI Test Method T205. Tensile strength, burst index, tearing index, and optical properties were measured following the TAPPI standard methods.

The edgewise compression properties were obtained from the FPL-developed vacuum compression apparatus (VCA). The VCA consists of a mechanism to apply a compression load to the edge of a paper specimen while preventing the paper from buckling out-of-plane to this load. This lateral support or force to hold the specimen flat is generated by vacuum holding the sample against movable support rods. The VCA is equipped with a load cell and extensometer to measure the applied load and strain, respectively (4). The load and strain values are collected via a PC-based data acquisition system. The test samples were cut to 95 by 27 mm from handsheets. All specimens were weighed and measured for thickness. The two ends (20 mm) of each specimen were sprayed with a clear aerosol lacquer and allowed to dry. This was done to reinforce the grip area of the specimens for subsequent clamping in the VCA. The samples were allowed to equilibrate in the test room for 24 h at 23°C, 50% RH before tests were conducted. The vacuum level in the VCA was at 50 to 60 kPa for all tests. The speed of the loading mechanism on the VCA was set to 1.5 mm/min. Ten specimens for each condition were tested.

Each test produces a complete load deformation curve to failure. The curves were recorded on an X-Y plotter and subsequently digitized (approximately 30 points per curve) to create stress-strain data for analysis. The combined data from 10 test curves for each CSF level were used to develop a composite stress-strain curve and then combine the three composite curves, one for each CSF level, to create a stress-strain composite curve for one experimental wood sample. The composite is determined by fitting the model \(y = c_1 \tanh \left( \frac{c_2}{c_1} x \right)\), suggested by Urbanik (5) to the combined data, where \(c_1\) is the slope of the curve at zero stress, \(c_2\) is a horizontal asymptote the curve approaches if extrapolated beyond the maximum stress, \(y\) = stress (MPa), \(x\) = strain (%), and \(\tanh\) = hyperbolic tangent.

**RESULTS AND DISCUSSION**

To achieve a pulp of target kappa number around 70 suitable for packaging grade paper, kraft pulping conditions of the seven different raw materials were similar except for cooking time (Table I). The only variable here was cooking time, which resulted in different pulp yield for different types of wood species.

Strength properties of handsheets prepared from each pulp were measured and compared. Burst index, tensile strength, and tear index of the different pulps are presented in Figures 1, 2, and 3, respectively, and compared at various CSF levels. Burst index and tensile strength, which are adhesion-based properties, follow the same order sequence except for DF-ST when the samples were compared. The LP-SRC pulp showed the highest burst index and tensile strength values followed by the other two lodgepole pine samples (LP-SML and LP-ST) at all CSF levels. Strength properties of DF-SML are between the LP group and WL-SML. WL-SML and WL/DF-SRC showed the lowest tensile strength values. But burst index of DF/WL-SRC was higher than DF-ST and WL-SML. The sequence of tearing index of the seven different pulps is virtually opposite to that observed for burst index and tensile strength. The WL-SML pulp showed the highest tearing index values compared with those of all other six pulps. This is followed by DF/WL-SRC, DF-SML, and LP-SML pulps, which showed middle tearing index values, although their burst and tensile index values were highest at all CSF levels. The LP-ST and LP-SRC showed the lowest tearing index although their burst index values and tensile strength values were high.

Figure 4 shows the variation of weighted average length values of seven pulps at various CSF levels. The WL-SML and DF/WL-SRC showed higher tearing index (Fig. 3) and higher length-weighted average values of fiber. This is due to the dependence of tearing index on fiber length. Besides fiber length, other fiber characteristics also play an important role on tearing index values. As observed from Figures 1 to 4, LP-SRC showed the highest burst index...
and tensile strength values and low tearing index value, although the pulp contains fiber of high weighted average length values.

Handsheet density, which is related to fiber flexibility and surface bonding area, is an important property that characterizes pulp properties. In general, pulp with higher flexibility and surface bonding areas shows higher handsheet density. Figures 5 and 6 show the relationship between handsheet density and various strength properties. For all pulp samples, burst index and tensile strength values increase with density. All pulp samples derived from the lodgepole pine group showed higher strength properties than those of other pulps in this study.

Figure 7 shows the kraft pulp yield of different wood samples and species. All pulps were prepared at 70 kappa number. Pulp yield varied up to 4% depending on types of sample and wood species. Kraft pulp yield of a specific wood sample is influenced by holocellulose and extractive contents while keeping the lignin in the same level. The DF-ST showed the highest pulp yield (54%), followed by LP-ST and LP-SML. The WL showed the lowest pulp yield at similar kappa level.

The important mechanical properties, such as burst index, tearing index, and tensile strength of the seven pulps compared at 450 mL CSF level and around 70 kappa number, are presented in Figure 8. Figure 8 clearly shows that all pulps from the lodgepole pine group give higher burst index and tensile strength values, whereas western larch and mixture of Douglas-fir and western larch give the higher tearing index values. The DF-ST and WL-SML gave similar burst index and tensile strength values, although kraft pulp yield of DF-ST was 4% higher than WL-SML. However, WL-SML shows higher tearing index than DF-ST, probably because of a higher number of fibers (due to lower yield) and weaker bonding because of lower hemicelluloses (due to lower yield). The results indicate that mechanical properties of kraft pulp depend on fiber characteristics in addition to pulp yield when compared in a similar kappa range.

Burst and tearing index of the pulps are plotted in Figures 9 and 10, respectively, as a function of tensile strength. As expected, Figure 9 shows a very good correlation between tensile strength and burst index values. After all, both burst index and tensile strength were adhesion-based properties. Burst index and tensile strength values were highest for LP-SRC and lowest for DF/WL-SRC. There was rarely any correlation of tearing index and tensile index values for different pulp samples (Fig. 10). Tensile strength mainly depended on bonding properties of fiber, whereas tearing index depended mostly on fiber lengths. Pulps that gave highest tearing index values showed lowest tensile strength and vice versa.

Figure 11 shows the compressive stress-strain composite curve for the test of seven different pulps. Stress and strain at failure are the end of the stress-strain curves. The compressive failure is based on failure data points only, i.e., the maximum stress and strain. The curve is a least squares fit of the model to all data points and is not forced through the main failure point. The strength values for different pulps have reached different levels of plateau before failure at different strain levels. For similar strain level, LP-SRC shows the highest stress values followed by LP-SML, DF-SML, LP-ST, DF-ST, DF/WL-SRC, and WL-SML in decreasing order. This is approximately the same order as is found in the case of burst index and tensile strength.

CONCLUSIONS

The kraft pulping process is suitable for small-diameter mature softwood species for production of packaging grade pulp. The burst index of all pulps lies between 6.5 to 8.7 kPa•m²/g. Tensile strength values of all pulps studied are between 17.5 to 23.5 kN/m² measured on the 205 g/m² handsheet. The burst index and tensile strength properties and VCA compression test dictate the suitability of pulp in packaging grade applications. Pulps derived from lodgepole pine gave the highest burst index and tensile strength values necessary for strong packaging grade materials. The composite stress-strain curve also showed the superiority of lodgepole pine pulps compared with the other pulps in this study. All other pulps in this series are also suitable for packaging grades products.

ACKNOWLEDGMENTS

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REFERENCES


Figure 1. Influence of CSF on handsheet burst index.

Figure 2. Tensile strength compared with CSF.
Figure 3. Tearing index compared with CSF.

Figure 4. Weighted average length of fiber compared with CSF.

Figure 5. Burst index compared with density.
Figure 6. Tensile strength compared with density.

Figure 7. Kraft pulp yield at 70 kappa level.

Figure 8. Mechanical properties compared with wood species.
Figure 9. Burst index compared with tensile strength.

Figure 10. Tearing index compared with tensile strength.

Figure 11. Composite curves for seven different pulps.
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