Development of Unbonded and Bonded Areas in Relation to *Populus* Species Wood Characteristics in Grinding

L.K. LEHTONEN, J.H. LEHTO and A.W. RUDIE

In terms of fibre development in mechanical pulping, most of the energy is spent on the creation of specific surface area. The total surface area created can be divided into two categories: surface area that adds to the unbonded area (optical properties) and surface area that adds to the bonded area (strength properties) of mechanical papers. This paper considers these two types of physical characteristics developed during grinding of Populus *species wood. Wood fibre characteristics are used to explain the variation of the development of bonded and unbonded areas. It is shown that the development of unbonded and bonded areas when grinding* Populus *species is a function of wood cell wall thickness, and thin-walled wood sources produce significantly higher unbonded and bonded areas at constant specific energy consumption. It is also shown that a constant specific energy consumption control philosophy does not compensate for changes in the wood characteristics.*

En ce qui concerne le développement de la fibre lors de la mise en pâte mécanique, la plus grande partie de l'énergie sert à créer une zone de surface spécifique. La surface totale créée peut être divisée en deux parties : celle qui ajoute à la surface non liée (propriétés optiques) et celle qui ajoute à la surface liée (propriétés de résistance) des papiers de pâte mécanique. Le présent article examine ces deux types de caractéristiques physiques développées pendant le défibrage de l'essence Populus*. Nous utilisons les caractéristiques des fibres pour expliquer les variations du développement de zones liées et non liées. Nous démontrons que le développement des zones liées et non liées lors du défibrage de l'essence* Populus *est en rapport avec l'épaisseur de la paroi des cellules ligneuses, et le bois dont les parois des cellules sont minces produit davantage de zones liées et non liées à une consommation constante d'énergie spécifique. Nous démontrons aussi que la philosophie de contrôle de la consommation constante d'énergie spécifique ne compense pas pour les changements constatés dans les caractéristiques du bois.*

INTRODUCTION

In mechanical pulping processes, fibres are separated from the wood matrix and then further deformed and broken into smaller particles to increase the total specific surface area of the pulp [1]. When the fibre web is formed, part of this total surface area bonds and part remains unbonded. The total amount of surface and the portion that is bonded are the main factors explaining the differences in light-scattering properties and most of the strength properties of mechanical pulps.

JPPS

L.K. Lehtonen
IPST at Georgia Inst. Technol.
500 10th Street NW
Atlanta, GA, USA
30332-0620
(lauri.lehtonen@ipst.edu)
J.H. Lehto
UPM Research Center
FIN-53200 Lappeenranta
Finland
A.W. Rudie
USDA Forest Service
Forest Prod. Lab.
One Gifford Pinchot Dr.
Madison, WI, USA
53726-2398

The pulp quality variation caused by varying wood quality in mechanical pulp production is reflected mainly in the tensile strength to scattering coefficient ratio. If it is assumed, in respect to tensile strength properties, that mechanical pulps are in a domain where fibre failure is negligible [2,3] then, at a constant fibre length, this ratio is dependent only on the ratio of bond strength to unbonded area of the paper. There are good indications that wood fibre characteristics play an important role in this [4–17]. However, due to the difficulty of estimating bonded area in mechanical pulps, these wood fibre characteristics have not yet been identified.

Sinkey [11] used a modified Page equation [18] to determine the development of bonded and unbonded area during the grinding and refining of two different wood species. He came to the conclusion that the development of the relative bonded area is independent of process but is strongly dependent on the wood raw material. Sinkey did not indicate what wood characteristics are responsible for this behaviour. However, he defined a linear relationship between the bonded and unbonded area of mechanical pulps (Eq. 1), wherein the constants S_0 and C are independent of the mechanical pulping process but dependent on the wood source.

$$S = S_0 + C \times T/L \qquad (1)$$

where

S = scattering coefficient m^2/kg, unbonded area (free surface area);
T = tensile index, Nm/g;
L = length-weighted fibre length, mm;
T/L = Sinkey bonded area, kN/g;
S_0 (m^2/kg) and C (m^2/MN) are wood source dependent constants.

In this study, the approach of Sinkey [11] was used to examine the important wood characteristics affecting the unbonded and bonded area development of various *Populus* species groundwood pulps. Due to the short fibre length of the *Populus* species and relatively low levels of bonding, it is reasonable to assume that fibre failure has an insignificant effect on the tensile strength of these pulps. It was also assumed that specific bond strength (bond strength per unit bonded area) was constant between pulps of different wood sources and specific energy consumption (SEC) levels.

The data used in this study are from the Lic. thesis of Lehto [5]. Lehto's objective was to mechanically pulp various *Populus* species and then use a multiple linear regression analysis to establish the important correlations between mechanical pulp sheet properties and wood fibre or chemical characteristics. The pulps were produced in a pilot pressurized grinder and the experimental details are recorded [5].

Unbonded and Bonded Area Development of Various *Populus* Species in Grinding

The data consist mainly of three specific energy levels per species. Only models with at least three SEC levels and with r^2 greater than 0.7 (T/L vs scattering coefficient) were selected for this study (Fig. 1). Linear models were also constructed for three species pulped by chemi-pressurized groundwood (CPGW), where alkaline peroxide was added into the shower water, as described in [5]. The following linear models with r^2 greater than 0.7 were accepted for further analysis (Table I). The data presented in Table I are only defined for the standard wet pressing pressure used to make the handsheets.

Relationship between Wood Fibre Properties and the Development of Bonded and Unbonded Area in Mechanical Pulps

The constant C represents the ratio of unbonded area to bonded area. As seen in Fig. 2, wood cell wall thickness had a positive correlation with the constant C. Thus, species with thick cell walls developed more unbonded area, at constant bonded area. This dependency on cell wall thickness became more pronounced when alkaline peroxide was added to the shower water (CPGW).

Due to the peculiar character of the constant C, it is of interest to define the ratio of the bonded area to the total surface area created in grinding. The ratio of bonded area to total area can be derived as follows:

$$C = (S - S_0)/(T/L) = U/B \quad (2)$$

where
U = developed specific unbonded area
B = developed specific bonded area

$$X = B/(U + B) \quad (3)$$

where
X = developed specific bonded area divided by total developed specific surface area

$$B = U/C \quad (4)$$

Combining Eqs. (3) and (4) results in:

$$X \text{ (bonded area/total area)} = 1/(C + 1) \quad (5)$$

TABLE I
SELECTED SPECIES. CONSTANTS S_0 AND C, r^2 AND WOOD CELL WALL THICKNESS

Species	S_0	C	*CWT*, µm	r^2	*n*
PGW					
P. tremula	66.4	0.29	3.065	0.90	3
P. tremula X tremuloides	68.9	0.26	2.67	0.92	3
P. balsamifera	60.0	0.31	3.12	0.98	4
P. grandidentata	65.8	0.27	2.85	0.95	3
P. maximowiczii X trichocarpa	50.5	0.38	3.795	0.71	4
CPGW					
P. tremula	56.8	0.35	3.065	0.81	3
P. tremula X tremuloides	71.4	0.19	2.67	0.98	3
P. tremuloides	41.4	0.64	3.49	1	3

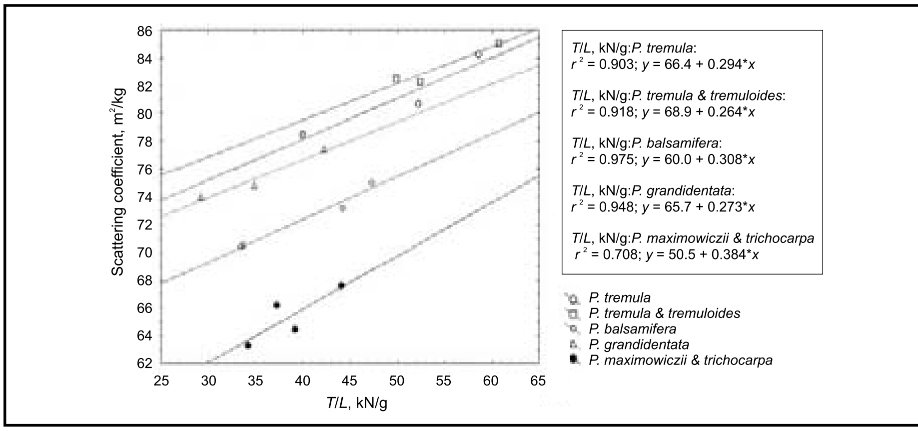

Fig. 1. Pressurized groundwood (PGW) pulps of various *Populus* species compared by the bonded (*T/L*) and unbonded (scattering coefficient) area development rate. Linear models with the r^2 are presented (data from [5]).

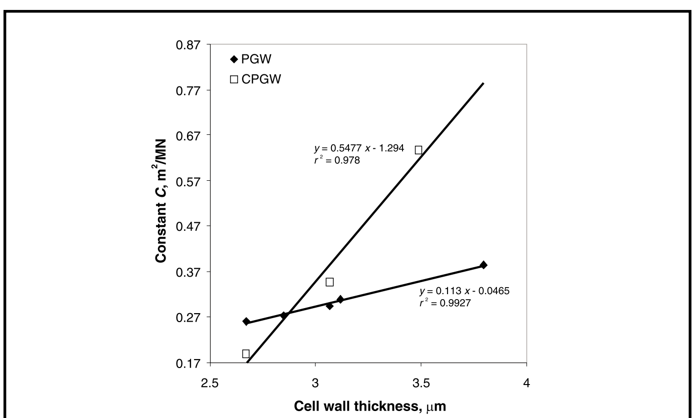

Fig. 2. Constant *C* vs wood cell wall thickness. CPGW series with a linear fit (r^2 = 0.978), and PGW with a linear fit (r^2 = 0.9927).

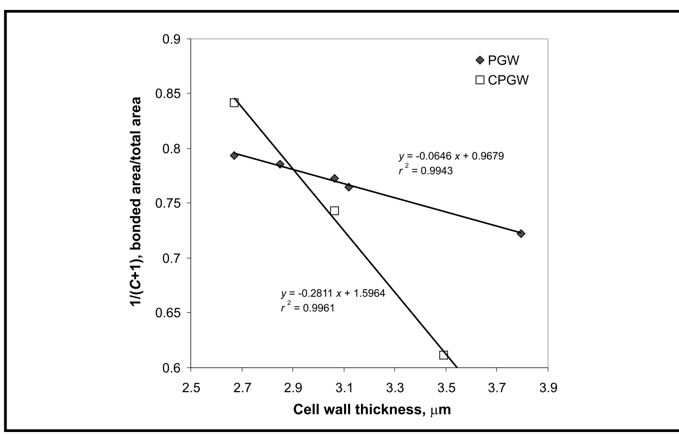

Fig. 3. Cell wall thickness vs developed bonded area divided by developed total area in grinding.

In Fig. 3, the ratio of bonded area development to total area development was plotted against wood cell wall thickness. Figure 3 shows that *Populus* species with thin cell walls developed more bonded area per total area than species with thicker cell walls. This indicates that the bonding potential of the surface area created in grinding is higher when wood with thin cell walls is used. This is consistent with the well-known phenomenon that fibres with thin cell walls are generally more collapsible [15,19] and thus likely more responsive to Campbell's forces, creating a more consolidated structure. It is also possible that thin-walled fibres experience more fatigue during grinding [20], which may increase the flexibility of the cell wall, consequently making the fibre more responsive to Campbell's forces. Another plausible explanation is related to the quality of finer material (middle fractions and fines) created in grinding [21]. However, the effect of cell wall thickness on the development of fibril-type – high bonding potential – fines is in contradiction to that observed in the refining of softwoods, where wood with thick-walled fibres produce fines with higher fibril-type fines content [8,15].

The effect of cell wall thickness on the ratio of bonded to total area was more pronounced as alkaline peroxide was added to the shower water during grinding (CPGW), as shown in Fig. 3. In aspen pulps, caustic charge affects the generation of surface area in mechanical pulping by reducing the amount of fines generated in the process [22]. Thus, it is possible that the observed increase in the cell wall dependency of the bonded area development divided by total surface area is due to the lower amount of fines present in the CPGW pulp, and the bonding properties of these pulps are governed more strongly by the bonding properties of the fibres.

Due to the relatively small constant C values obtained for all the various wood sources used in this study, constant S_0 was more responsible for explaining the differences between the species. Figure 4 depicts the way constant S_0 correlated negatively with the cell wall thickness. This suggests that the thin-walled *Populus* wood species, when ground to the same bonded area, end up with higher unbonded areas due to their high S_0 constants.

Using a few geometrical simplifications, where the fibre is assumed to be a cylinder with length (L) and diameter (W) and lumen diameter of ($W - 2CWT$), the originally available specific surface area of the wood fibres can be estimated from the cell wall thickness of the fibre. The derivation is shown in the appendix and eventually results in an equivalent equation to that of Scallan and Borch [23].

Equation (12) states that the specific surface area of fibre is a function only of cell wall thickness. This suggests a reasonable physical explanation for the constant S_0, which seems to be dependant on the initial specific surface area of the fibre before any energy is applied into the wood matrix. This is shown in Fig. 5, where the specific surface area (SA_f) was calculated for PGW samples using a cell wall density of 1500 kg/m^3 and plotted against the constant S_0. Another interesting observation is related to the fact that the linear fit seems to go through the origin. This agrees well with the results of Gurnagul et al. [24], who found the same relationship to apply for hardwood chemical pulps, as well as Scallan and Borch [23], Haselton [25] and Rennel [26], who all showed that total unbonded surface area is closely related to the scattering properties of chemical and mechanical pulps.

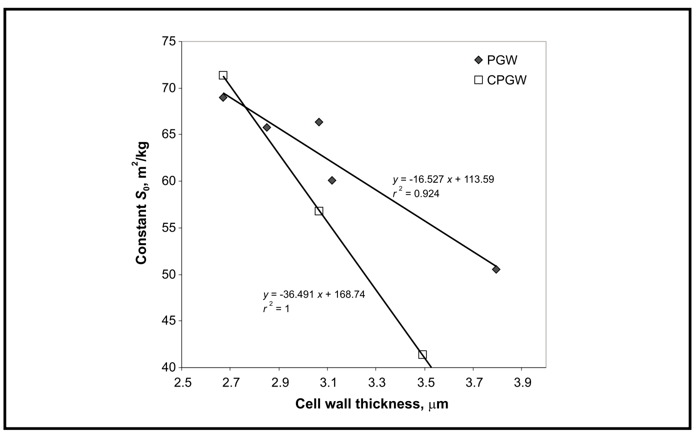

Fig. 4. Constant S_0 vs wood cell wall thickness.

SEC in Relation to Relative Bonded Area Development and Cell Wall Thickness

It is widely accepted that wood characteristics are one of the most significant factors affecting the quality of mechanical pulps. However, at times, there are discussions whether it is possible to utilize alternative pulping strategies to treat fibres with different characteristics so that the end quality of the pulp produced remains the same. Many mills today run with a constant SEC philosophy to avoid disturbances caused by incoming wood raw material and to keep the product quality constant. Figure 6 shows the dependency of SEC on the variables scattering coefficient (unbonded area) and T/L (bonded area). The r^2 ($P < 0.0001$) of the SEC dependency on T/L and scattering coefficient is 0.49, using a linear model. The black straight lines ($r^2 = 0.917$) in the figure are constant cell wall thickness lines from the modelled linear relationships. Figure 6 shows distinctly that the constant SEC philosophy does not compensate for raw material variation in terms of unbonded and bonded area. It also shows that it is not possible, by altering the SEC, to reach the same unbonded and bonded areas when the wood raw material cell wall thickness changes. Another interesting implication is that, at the same bonded area, a 29% decrease in wood cell wall thickness (3.5 vs 2.5 μm) results in a 15% increase in scattering coefficient (unbonded area), and all this with significantly lower (29%) SEC (Fig. 6).

The higher SEC associated here with thick cell wall *Populus* species wood to obtain high unbonded and bonded areas is likely related to the fatigue behaviour of wood. The poor energy efficiency of the grinding process

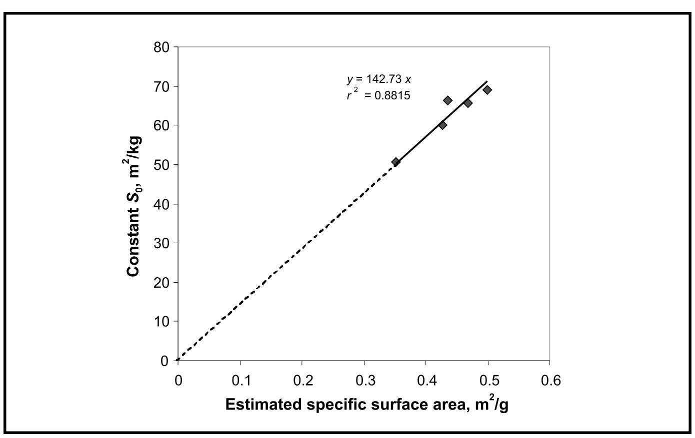

Fig. 5. Wood fibre calculated specific surface area vs constant S_0 for *Populus* PGW pulps.

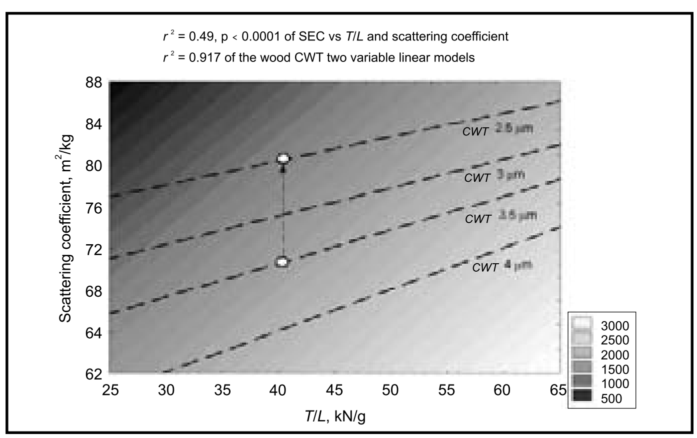

Fig. 6. The development of unbonded area as a function of bonded area of wood species with various cell wall thicknesses at various SECs.

is believed to be due to the high proportion of energy consumed in elastic deformation of the wood structure and, to induce weakening of the wood structure, the matrix needs to be compressed into its plastic regime [20]. The results obtained here imply that wood with thin cell walls is more readily compressed into its plastic regime and thus more compliant to fatigue.

CONCLUSIONS

This paper considered two types of physical characteristics developed during grinding of *Populus* species wood: bonded and unbonded areas. Wood fibre properties were used to explain these two characteristics. The development of unbonded and bonded areas when grinding *Populus* species is mainly a function of wood cell wall thickness. At a constant total created specific surface area, *Populus* species with thin cell walls develop more surface area that is capable of bonding than species with high cell wall thicknesses, which is likely due to the higher compliance of thin-walled fibres to Campbell's forces. At constant SEC, species with low cell wall thicknesses have significantly higher bonded and unbonded areas. This indicates that wood with thin cell walls is more prone to experience fatigue in the grinding process.

In addition, there are two important practical implications resulting from this work. First, it is shown that a constant SEC control strategy cannot compensate for raw material variation. Secondly, with respect to papermaking potential and energy consumption, low wood cell wall thickness is beneficial in the grinding of *Populus* species.

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APPENDIX

The specific surface area of a fibre:

$$Sa_f = [LW\pi + L\pi\,(W - 2\,CWT)]/m_f \qquad (6)$$

where
SA_f = specific surface area of fibre with lumen area
L = fibre length
W = fibre diameter
CWT = fibre cell wall thickness
m_f = mass of fibre

$$Sa_f = \pi\,L\,(2W - 2\,CWT)/m_f \qquad (7)$$

Fibre coarseness:

$$C_f = m_f/L \qquad (8)$$

$$C_f = CWA \times D \qquad (9)$$

where
CWA = cross-sectional cell wall area
D = cell wall density

Combining Eqs. (7) and (8) results in:

$$Sa_f = \pi(2W - 2CWT)/C_f \qquad (10)$$

$$CWA = \pi(CWT \times W - CWT^2) \qquad (11)$$

where
CWT = cell wall thickness
CWA = cross-sectional cell wall area

Combining Eqs. (9), (10) and (11) results in:

$$SA_f = 2/(CWT \times D) \qquad (12)$$

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