PREDICTION OF THE HEARTWOOD CONTENT OF PINE LOGS

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ABSTRACT

The heartwood content of pine is discussed in terms of age, size, and shape of the log. The physical properties of heartwood and sapwood were analyzed. An exact formula was developed for the volume proportion of heartwood as a function of mass density of the log. A formula for the area proportion of heartwood within a cross section at the upper end of a log as a function of the volume proportion of heartwood within the log is given. The two formulae are combined to a predictive model of the heartwood content within a pine log.

Keywords: Age, size, shape, mass density, water content, sapwood content, predictive model.

INTRODUCTION

For many tree species, liquid and gas permeability of heartwood is less than the permeability of sapwood (Johansson 1977; Koponen 1982). In some species, heartwood includes chemical constituents that inhibit fungal activity (Grönlund et al. 1979; Rennerfelt 1947; Erdtman et al. 1951). These two properties make heartwood a material with natural resistance to decay. Heartwood with a high content of extractives also has greater dimensional stability when subjected to fluctuations in relative humidity (Trendelenburg 1939; Rennerfelt 1947; Kärkkäinen 1985).

Wood products made of heartwood, or wood products with a high heartwood content, may be produced in several ways. However, the production processes can be made more efficient if the heartwood content of the logs is known.

Heartwood content can not be measured directly within a high-speed production line at the sawmill. This study investigated methods for the prediction of heartwood content of pine sawlogs on the basis of readily measurable attributes. Such methods must be based on correlations between heartwood content and some easy-to-observe properties of logs. The correlations may be due to mechanisms that regulate physiological changes within a tree, or due to interrelationships between the physical properties of wood and the properties of the log.

Heartwood formation apparently takes place only in trees over a certain age, and thereafter the proportion of heartwood increases with age (Schwappach 1892; Pilz 1907; Lappi-Seppälä 1952; Eneroth 1922; Trendelenburg 1939). Some previous observations indicate that the amount of heartwood in terms of the number of annual rings can be predicted on the basis of the total number of annual rings (Pilz 1907; Trendelenburg 1939). Unfortunately, knowledge of the amount of heartwood in terms of annual rings is of limited technical value; knowledge of the size of the heartwood zone measured in centimeters would be more

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useful. Previous investigations suggest that this variable cannot be predicted accurately on the basis of cambium age (Eneroth 1922; Trendelenburg 1939).

Some studies suggest that the diameter of a pine butt log may be correlated with the heartwood content of the log (Kärkkäinen 1972; Carrodus 1972; Kellomäki 1981). The size of the butt log obviously is related to the maturity of the tree. However, large butt log size also may be related to high growth rate, which in turn, corresponds to low heartwood content (Schwappach 1892; Trendelenburg 1939; Lappi-Seppälä 1952; Kuylenstierna 1967). Thus, a positive correlation between log diameter and heartwood proportion is not particularly strong (Kärkkäinen 1972, cf. Kellomäki 1981).

In this paper, the cross-sectional area proportion of heartwood within a log as a function of log age, size, and shape is discussed. Then, a further analysis of the physical properties of heartwood and sapwood is presented. A formula for the volume proportion of heartwood as a function of mass density of the log is given. Then, a formula for the cross-sectional area proportion of heartwood at the upper end of a log, as a function of the volume proportion of heartwood within the log, is given. The two formulae are combined to form a predictive model. Variation of the model parameters with changing seasons is discussed.

MATERIALS AND METHODS

The experimental material consisted of two independent sets of data. Dataset 1, acquired in March 2000, included 100 Scots Pine (*Pinus sylvestris* L.) butt sawlogs that entered a sawmill in Eastern Finland. Sampling was designed to represent the diameter distribution and geographic yield of Kainuu Province. Sample disks were sawn 55 cm from the top of any sampled butt log, the logs being 3 to 6 m long. Circular specimens 28 mm in radial and tangential diameter were cut from the disks, along a sampling line corresponding to the greatest diameter of the disk. Three specimens were produced from each disk, two representing heartwood and one representing sapwood.

Dataset 2, acquired in August 2000, consisted of 40 logs sampled from the same sawmill as Dataset 1; these logs also represented the diameter distribution and geographic yield of Kainuu Province. From these logs, sample disks were sawn at 10%, 30%, 50%, 70%, and 90% of log length, and specimens were produced as for Dataset 1. The green volume and the dry mass of each specimen were determined, as well as the average width of the annual rings.

For each sample disk, a system of coordinates was established by taking the line of greatest diameter as reference line and the midpoint of this line as the origin. The distance of the heartwood-sapwood boundary, as well as that of the wood-bark boundary, was determined at angular intervals of 30°. The location of the geometric center of the heartwood, the center of the log cross section, and the location of the pith of the tree were determined. The cross-sectional area of each wood disk and the cross-sectional area of the heartwood were determined based on the average distance of the 12 boundary points from the center of the disk and from the center of the heartwood, respectively.

Heartwood content as a function of age, size and log shape

Pine heartwood begins to form at a finite age, and then the heartwood content increases with age. Heartwood formation represents a phase transition from tissue that includes living cells to a tissue that no longer contains living cells. As a theoretical limit, a tree becomes so old that it can no longer metabolize, the heartwood proportion approaches unity. Thus the proportion of heartwood must differ from zero at finite maturity and approach unity as age approaches infinity.

There are many models that may satisfy the above requirements. One of the simplest is

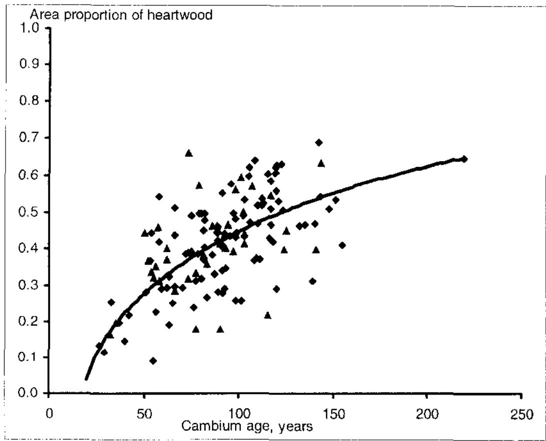

FIG. 1. The heartwood cross-sectional area proportion within wood disks taken from the vicinity of the upper end of butt log, as a function of the number of annual rings in any disk. Dataset 1 is plotted as diamonds and Dataset 2 as triangles. Eq. (1) is fitted to Dataset 1 (diamonds).

$$\textit{heartwood proportion} = \begin{cases} 0, & \text{if age} < a, \\ 1 - \exp\left[-\left(\dfrac{\text{age} - a}{b}\right)^c\right], & \text{if age} \geq a, \end{cases} \quad (1)$$

where a and b are constants with the dimension of age (time), and c is dimensionless constant. The physical interpretation of the constant a is the cambium age at which heartwood formation begins. The constant b determines the age scale of the increment in the proportion of heartwood. The dimensionless constant c accounts for the geometrical shape of the increment in heartwood proportion as the values of the dimensionless combination (age − a)/(b) increase.

Figure 1 shows the top disk observations for Datasets 1 and 2, as well as a fit of Eq. (1) to Dataset 1. The coefficient of determination of Eq. (1) in Dataset 1 is 0.46. Dataset 2 displays somewhat more scatter, but both datasets display a similar trend for increase in the proportion of heartwood with cambium age.

The significant residual variation seen in Fig. 1 indicates that cambium age would not be a practically useful indicator of heartwood content, even if it could be detected readily during sawmilling operations. The residual variation in Fig. 1 correlates positively with disk (or log) diameter, which agrees with findings reported in the literature (Werberg 1930; Kärkkäinen 1985). However, the residual variation in Fig. 1 correlates negatively with annual ring width in the sapwood. Thus, the positive effect of increasing size at a specified age can not be taken simply as an effect of growth rate (cf. Kärkkäinen 1972, 1976, 1985; Kellomäki 1981).

Not only does the cambium age not appear to predict heartwood content accurately, it also is too time-consuming to detect in industrial situations. Therefore, we will consider the merits of using log (or disk) diameter as an independent variable.

Heartwood formation appears to start at a finite size, and then increases as the tree grows. On the other hand, the size increases as the tree matures. Once a tree becomes so old that it can no longer metabolize, the proportion of heartwood approaches unity. Thus, the heartwood proportion must differ from zero at a finite size, and approach unity as the tree size becomes very large.

Many models may satisfy the above requirements. One of the simplest is

$$\textit{heartwood proportion} = \begin{cases} 0, & \text{if size} < d, \\ 1 - \exp\left[-\left(\dfrac{\text{size} - d}{e}\right)^f\right], & \text{if size} \geq d, \end{cases} \quad (2)$$

where d and e are constants with the dimension of size, and f is a dimensionless constant. The physical interpretation of the constant d is the size at which heartwood formation is initiated. The constant e determines the size scale of the increment in the proportion of heartwood, and the dimensionless constant f accounts for the geometrical shape of the increment in heartwood proportion with increas-

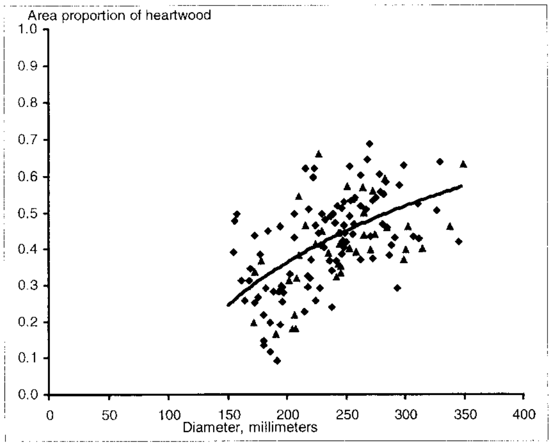

FIG. 2. The heartwood cross-sectional area proportion within wood disks taken from the vicinity of the upper end of butt log as a function of the diameter of any disk. Dataset 1 is plotted as diamonds and Dataset 2 as triangles. Eq. (2) is fitted to Dataset 1 (diamonds).

ing values of the dimensionless combination (size $-$ d)/e.

Figure 2 shows the top disk observations for Datasets 1 and 2, as well as a fit of Eq. (2) to Dataset 1. The coefficient of determination of Eq. (2) in Dataset 1 is 0.31. Both of the datasets display a similar trend, heartwood content increasing with disk diameter.

The residual variation from Fig. 2 is strongly and negatively correlated with sapwood annual ring width, and positively with the number of annual rings. The latter observation is in agreement with findings reported in the literature (Werberg 1930; Kärkkäinen 1985).

Log diameter can readily be determined during the course of the sawmilling process. However, as the coefficient of determination for the heartwood proportion is only 0.31, this measure is hardly of practical value in estimating the proportion of heartwood.

Some observations suggest that log taper may be slightly correlated with the heartwood proportion in butt logs (Lappi-Seppälä 1952; Kellomäki 1981). A slight positive correlation was also found in this study, but this correlation was much lower than that between size and heartwood content.

Heartwood content as a function of mass density

Heartwood formation in conifers typically involves a decrease in wood moisture content. More than half of the green mass of pine sapwood consists of water, whereas the water content of heartwood is rather low. Thus, the green mass density of sapwood is often about twice the green mass density of heartwood (Trendelenburg 1939; Kärkkäinen 1985; Zobel and van Buijtenen 1989), where green mass density is the ratio between mass and volume in the green condition.

Since heartwood content is the dominating factor in the variation of green density within a log, the mass density of the log may be given as

$$\rho = h_v\rho_h + (1 - h_v)\rho_s, \tag{3}$$

where h_v is the volume proportion of heartwood, ρ_h is the mean mass density of heartwood and ρ_s is the mean mass density of sapwood.

The volume proportion of heartwood can be readily solved from Eq. (3) as

$$h_V = \frac{\rho_s - \rho}{\rho_s - \rho_h}. \tag{4}$$

The volume proportion of heartwood within any log, as the weighted mean of the heartwood contents of the five disks produced from each log, can be determined for Dataset 2. Furthermore, the density of any log of Dataset 2 can be calculated as the weighted mean of the mass densities of the 15 wood specimens extracted from any log. The relationship between the mass density of a log and the corresponding volume proportion of heartwood in the log is shown in Fig. 3.

We find from Fig. 3 that the density of each log can be used to predict the volume proportion of heartwood far better than age or size did for the cross-sectional proportion of heartwood (cf. Figs. 1 and 2). The coefficient of determination of Eq. (4) in Dataset 2 is 0.77. Another benefit of Eq. (4) is that the parameters determining the relationship shown in Fig. 3 have a sound physical interpretation. In

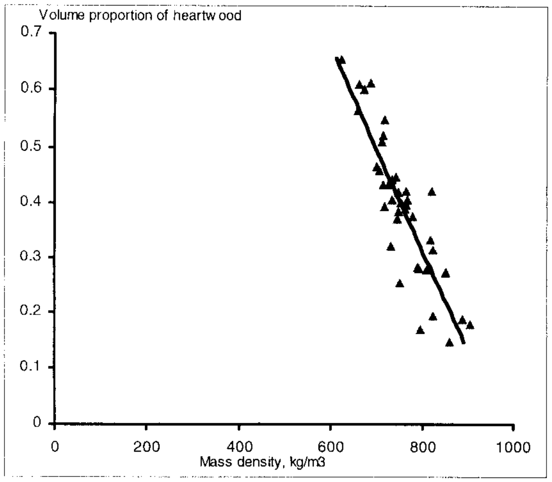

FIG. 3. The volume proportion of heartwood within the logs of Dataset 2 as a function of the mass density of a log. The function line corresponds to Eq. (4).

the experimental material, the mean mass density of sapwood, ρ_s, equals 972 kg/m^3, and the difference in density between sapwood and heartwood, $\rho_s - \rho_h$, is 551 kg/m^3.

An eventual problem in utilization of the result shown in Fig. 3 is that from the viewpoint of sawmilling, the properties of the narrowest part of a log are crucial. Thus, the heartwood content of a log cross section taken from the top end of the log is of particular interest. This will be discussed in the following section.

Heartwood content on volume and area basis

As a theoretical limit, a tree that becomes so old that it can no longer metabolize has no sapwood. Thus, in the case of vanishing metabolism, the limit value for the heartwood proportion is unity. The same limit value applies to volume proportion as well as to cross-sectional area proportion.

On the other hand, observations suggest that in the case of mature but still vital trees, the greatest heartwood content is found in 20% . . . 30% of the tree length (Werberg 1930; Lappi-Seppälä 1952; Kärkkäinen 1985). Thus, in many cases the cross-sectional area proportion of heartwood at the top of the butt log is greater than the volume proportion of heartwood in the butt log.

A third important observation is that in the case of young trees, heartwood formation begins near the butt of the tree. Thus, in the case of young trees, the volume proportion of heartwood is greater than the area proportion within a cross section located at the height of 4 . . . 6 m. Furthermore, the volume proportion of heartwood within the "butt log" has a nonzero finite value when the area proportion within the cross section at 4 . . . 6 m height first differs from zero.

Construction of a physically justified model that meets the above requirements is not straightforward. The area proportion of heartwood h_A must first differ from zero at a nonzero value of the volume proportion of heartwood h_V. The value of h_A must then increase with increasing h_V, at some stage exceeding the corresponding value of h_V. Finally, once h_V approaches unity, h_A must approach unity. One of the simplest functions satisfying these requirements is

$$h_A = 0, \quad \text{if } h_V < 1 - \frac{g}{[\ln(1 + l)]^{1/k}}$$

$$1 - h_A = \frac{1}{\exp\left[\left(\frac{g}{1 - h_V}\right)^k\right] - l}, \quad \text{if } 1 - \frac{g}{[\ln(1 + l)]^{1/k}} \leq h_V < 1, \tag{5}$$

where h_A is the cross-sectional area proportion of heartwood in the vicinity of the top end of the log, and g, k and l are dimensionless constants.

From Fig. 4 we find that the experimental observations regarding $1 - h_V$ and $1 - h_A$ are closely related. Eq. (5) gives a coefficient of determination of 0.95. Now, Eq. (5) can be substituted to Eq. (4). Since the coefficient of determination of Eq. (5) is close to unity, the coefficient of determination of the combined

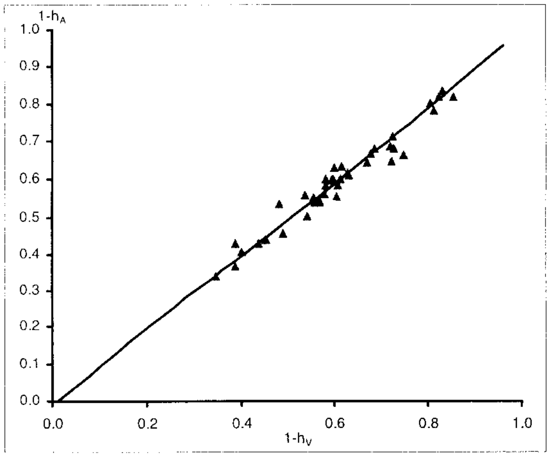

FIG. 4. The cross-sectional area proportion of sapwood in the vicinity of the upper end of a log as a function of the volume proportion of sapwood within the log in Dataset 2. The function line corresponds to Eq. (5).

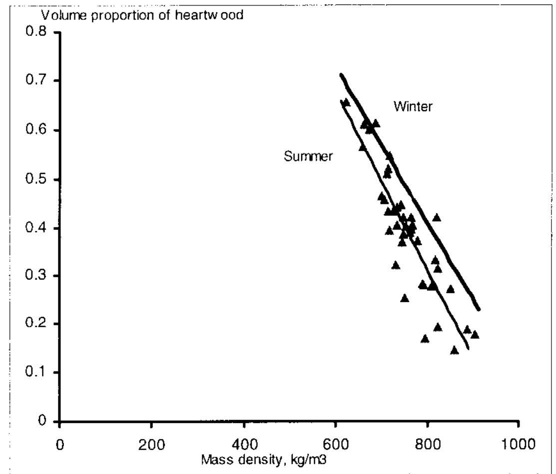

FIG. 5. The change in the outcome of Eq. (4) as a function of seasonal variation in density. Solid lines refer to Eq. (4) in summer and winter. Plotted data correspond to Dataset 2, collected in summer.

function is not far from that of Eq. (4); for the present material it is 0.76.

DISCUSSION

We found that prediction of the heartwood content of a sawlog on the basis of the mass density of the log is far more accurate than predictions based on size, age, or shape. We also found that Eq. (5) obviously is rather robust; in addition to having a high coefficient of determination, it is insensitive to seasonal variations in moisture content and density since it contains only geometric variables. However, complications may appear with Eq. (4) if the parameters ρ_s and $\rho_s - \rho_h$ vary in an unknown way. Obviously, these parameters, having the dimension of mass density, may vary with the seasons.

The experimental material allows us to deal with such seasonal variation. Dataset 1, being collected in winter, and Dataset 2, collected in summer, may reveal any eventual variation in mass density due to season. The mean sapwood density in the experimental material was 9% higher in winter than in summer. The difference between the mean values for sapwood density and those for heartwood density was 15% greater in winter than in summer. The effect of such changes on the outcome of Eq. (4) is shown in Fig. 5.

From Fig. 5 we see that seasonal variations in density should be considered. In winter, a specified mass density of a log corresponds to a greater heartwood content than in summer. The relative difference between seasons is the greater the smaller is the heartwood content.

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