THERMAL MODIFICATION OF COLOR IN RED ALDER VENEER. I. EFFECTS OF TEMPERATURE, HEATING TIME, AND WOOD TYPE

Derek W. Thompson
Graduate Student

Robert A. Kozak
Associate Professor

and

Philip D. Evans†
Professor
Centre for Advanced Wood Processing
Department of Wood Science
University of British Columbia
Vancouver, BC, Canada V6T 1Z4

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ABSTRACT

Red alder has become one of the most widely traded hardwood species in North America, and sliced red alder veneer is commonly applied as a decorative overlay on composite wood panels used by the furniture and cabinet industries. Red alder wood, however, acquires a mottled orange color following felling, which is undesirable when the wood is used for decorative purposes. Heating red alder wood remedies this problem to some extent, but there is still an unacceptable level of variability in the color of veneer sliced from heated veneer cants. This study examined the variation in color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions. The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening can explain variation in color of veneer sliced from steamed red alder cants, and to determine the optimal thermal treatment (temperature and time) that can impart the tan color to red alder wood that industry is seeking. Results indicated that there was within-tree variation in the color of red alder samples following thermal treatment, but differences were pronounced only when wood was heated at a low temperature. Wood close to the bark tended to be redder than wood close to the pith when heated at 30°C, but such a difference was absent in wood heated at higher temperatures (50–90°C). Heating red alder wood, *in vitro*, at 70°C for 36 h produced wood that was evenly colored from pith to bark and matched the current industry color preference. It is suggested that the color of thermally modified red alder wood depends on the strength of reactions that produce orange/red chromophores in the wood, thermal darkening of the wood, and destruction of orange/red chromophores.

Keywords: Red alder, veneer, color, thermal modification.

INTRODUCTION

Red alder (*Alnus rubra* Bong.) has become one of the most economically important hardwood species in North America (AHEC 2003). Sliced red alder veneer is commonly used as a decorative overlay on composite wood panels (particleboard and medium density fiberboard), which are then used in the manufacture of cabinets and furniture (Hibbs et al. 1994). Red alder wood, however, acquires a mottled orange color after felling, which is undesirable when the wood is used for cabinets and furniture (Kozlik 1987; Kaufmann 2003; Simpson 1991). To over-

† Member of SWST.

come this problem, sawn alder lumber is steamed at temperatures of 66° to 100°C for varying periods of time (Kozlik 1962, 1967, 1987; Kozlik and Boone 1987). Steaming produces a uniform tan color on the surface of red alder lumber, but no studies have examined the thermal modification of color in red alder veneer cants. Industry reports, however, suggest that it is much more difficult to achieve color uniformity in veneer sliced sequentially from steamed cants (Kaufmann 2003). Radial variation in wood color in the cants, possibly caused by thermal gradients within veneer cants during steaming, could explain such variability. Alternatively, within-tree variation in the susceptibility of red alder to thermal discoloration could be responsible for the variation in color of sliced veneer. Variability in the color of sliced veneer is highly undesirable because veneer sheets pressed onto composite wood panels need to be color matched to meet the demands of consumers for red alder furniture and cabinets with uniform color (Raettig et al. 1995).

This study examined the variation in color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions using four temperatures (30°, 50°, 70°, and 90°C) and five heating times (8, 24, 36, 48, and 72 h). The aim was to examine whether within-tree variation in the susceptibility of red alder wood to thermal darkening can explain variation in color of veneer sliced from steamed red alder cants, and secondly to determine the optimal thermal treatment (temperature and time) that can impart the favored tan color to red alder wood.

LITERATURE REVIEW

The majority of research on the discoloration of wood at ambient temperatures and thermal modification of wood color has been undertaken in order to eliminate the discoloration of wood that can occur during the kiln-drying of lumber. Few studies have focused directly on the thermal modification of wood color in veneer cants, despite the widespread presteaming of such cants prior to veneer slicing. The results of several studies that have examined color changes in wood at ambient and elevated temperatures, however, are relevant to the thermal modification of color in veneer cants.

Changes in the color of wood can occur at ambient temperatures as a result of enzyme-mediated (Maillard) reactions between sugars, phenolic compounds, and amino acids. These reactions, which are similar to the ones causing the browning of freshly cut fruit, occur in living parenchyma cells where they create amorphous globules of colored material (Yeo and Smith 2004). Simpson (1991) described a red to orange discoloration that occurs in freshly cut red alder wood and suggested that it was due to an oxidative reaction between extractives and the atmosphere. Abe et al. (1994) also suggested that the reaction between extractives and atmospheric oxygen under weakly alkaline conditions was responsible for color changes in freshly cut sugi (*Cryptomeria japonica* (L.f.) Don) wood. They concluded, however, that enzymes were not responsible for the color changes. Enzymatic reactions, however, were thought to be responsible for the mottled discoloration of several species upon exposure of green wood to oxygen (Hon and Shiraishi 1991).

The discoloration of wood during kiln-drying has also been linked to Maillard reactions, although heat applied during drying may cause colored compounds to darken and migrate towards the surface of boards as free water is removed during drying. Kapp et al. (2003) suggested that Maillard reactions were responsible for kiln brown and yellow stain of South African grown pine species (*Pinus elliottii* Engelm, *P. patula* Schlecht and Chamisso, and *P. taeda* L.) during kiln-drying. They noted a distinct transition from yellow to brown stain as the drying temperature exceeded 80°C. McDonald et al. (2000) also suggested that Maillard reactions were responsible for the chocolate brown discoloration of radiata pine (*Pinus radiata* D. Don) sapwood during drying. The degree of discoloration was thought to be dependent on the chemical composition of extractives, wood pH, and drying temperature.

Heat can directly alter the color of wood by

causing hydrolysis and oxidation of wood components. According to White and Dietenberger (2001), darkening of wood due to heat is caused by thermal degradation of hemicelluloses and lignin, and can commence at temperatures as low as 65°C, depending on wood pH, moisture content, heating medium, exposure period, and species. Hence, hydrolysis of hemicelluloses can occur at temperatures within the range employed to kiln-dry timber, and several studies have examined the discoloration of hardwoods during drying. Kollmann et al. (1951) found that temperatures and relative humidities in excess of 50°C and 65% RH were required to produce a red color change in maple (*Acer sp.*) and beech (*Fagus sp.*). Millett (1952) found that drying temperatures of 65°, 80°, and 90°C produced a brown color in sugar pine (*Pinus lambertiana* Dougl.), oak (*Quercus sp.*), and spruce (*Picea sp.*), respectively, when the relative humidity during drying was 65%. Sundqvist (2002) exposed white birch (*Betula pubescens* Ehrh.), Scots pine (*Pinus sylvestris* L.), and Norway spruce (*Picea abies* L.) to temperatures of 65°, 80°, and 95°C for 0, 1, 3, and 6 days. Each species showed pronounced darkening when the temperature exceeded 80°C. The duration of heat treatment was more important than temperature in changing the color of birch, whereas both factors were of similar importance in altering the color of pine and spruce. Thomassen (1986) cited by Stenudd (2004) found a brown-red discoloration of the core of European beech (*Fagus sylvatica* L.) boards during convection drying at ~40°C. Discoloration occurred when the wood reached fiber saturation point (25 to 35% moisture content). Stenudd (2004) reached the same conclusion when examining the discoloration of silver birch (*Betula pendula* Roth.) during kiln-drying. Recently, Yeo and Smith (2004) found that internal darkening of hard maple (*Acer saccharum* Marsh.) developed at or above 43°C when wood moisture content was at or above fiber saturation point.

Discoloration of wood during kiln-drying is generally regarded as a defect; however, heating of wood is sometimes deliberately employed to change wood color. Brauner and Conway (1964) found that color change in black walnut (*Juglans nigra* L.) was most noticeable when the wood was steamed at between 100 and 110°C for 4 to 6 h. Charrier et al. (2002) immersed walnut logs in water at temperatures of 80° to 90°C for up to 51 h and then measured color changes in sapwood and heartwood using a spectrophotometer. They found that the thermal treatments promoted the darkening and reddening of the wood, but the darkening was more prominent in heartwood than in sapwood. Kozlik (1962) found that presteaming red alder lumber at 88° to 93°C for 11 to 12 h resulted in wood with the best color uniformity. Kozlik (1967) tested several combinations of temperatures and heating times during the drying of red alder, but none of them were able to achieve both color uniformity and absence of sticker stain. A subsequent study, however, found that steaming red alder lumber at 100°C for at least 4 h (before air- or kiln-drying) eliminated sticker stain and prevented mottling (Kozlik 1987). Kozlik and Boone (1987) found that steaming red alder lumber at 99°C for 6 h during kiln-drying produced boards with the desired quality, color uniformity, and moisture content. However, to improve color uniformity, Kozlik (1987) recommended that red alder lumber should be presteamed for at least 12 h at 66°C to 77°C, with the duration of steaming increasing as initial moisture content decreased. It should be noted that observations by Kozlik and Boone (1987) are relevant only to surface discoloration of red alder lumber, and they did not examine subsurface color changes in logs or cants, which are of greater importance for wood used for the production of sliced veneer.

MATERIALS AND METHODS

Sample preparation

Four red alder trees growing in the Malcolm Knapp Research Forest in Maple Ridge, British Columbia, were selected based on similarities in their height (18–25 m), diameter (25–32 cm at breast height), age (26–31 years), and growing conditions (non-riparian). Trees growing in riparian zones (adjacent to streams) were avoided,

as harvest restrictions in British Columbia limit the removal of any species in or adjacent to such areas. A single tree was sampled each week over a period of 4 weeks in August 2003 (4 trees in total). Thus, each tree and sampling period acted as a separate replication.

Trees were marked at breast-height (1.3 m above ground level), felled, and inspected for the presence of abnormalities such as rot or scarring. Four cross-sectional discs were cut from each tree: two immediately above and two immediately below breast-height (Fig. 1). Each disc was 15 cm thick (longitudinally) and was free from internal rot or scarring. The four discs were randomly assigned a letter (A, B, C, or D) and immediately transported to the laboratory for further processing.

Five quarter-sawn slats were cut from each of the four discs using a bandsaw. Slats were 1 cm wide (tangentially) and cut from bark to pith (Fig. 1). The moisture content of separate pith-to-bark samples, expressed as a percentage of their oven-dry weight (obtained by oven-drying samples overnight at 105°C), was found to vary from 95 to 127%. The location of each slat was randomly selected on the outer circumference of the disc prior to sawing. A 1- × 1-cm pith-to-bark sample was then cut from the middle (7 cm from top and bottom) of each slat resulting in five 1- × 1-cm samples from within each disc. Each sample was sealed in an 8- × 23-cm sheet of aluminum foil to reduce the rate of drying of samples during heating, labeled with the appropriate disc letter (A–D) and randomly assigned a treatment number (1–5) (Fig. 1).

Thermal treatments and color measurement

Samples obtained from the same discs were allocated to the same treatment temperature. Thus, samples from discs A, B, C, and D were subjected to thermal modification at temperatures of 30°, 50°, 70°, and 90°C, respectively. The 5 samples from within each disc were randomly allocated to the different heating times, 8, 24, 36, 48, and 72 h.

Samples were placed in 25- × 200-mm test tubes that were submerged in preheated glycerol baths set at 30°, 50°, 70° or 90°C. Each test tube was covered, but not completely sealed, to avoid pressure build-up. Samples were removed from the tubes after heating and allowed to cool at room temperature for 30 min. They were then unwrapped from the aluminum foil and cross-cut every fifth growth ring starting at the pith and finishing in the outer sapwood. Thus, five subsamples were produced from each pith-to-bark sample, each containing five growth rings with the earlywood exposed longitudinally. Exposed earlywood faces were allowed to dry for 24 h at room temperature and their color was then measured using a spectrophotometer (Minolta CM-2600d). Earlywood was chosen for color measurements as it forms the majority of the wood in red alder (Parker et al. 1978). A total of 400 color measurements were made. Color is ex-

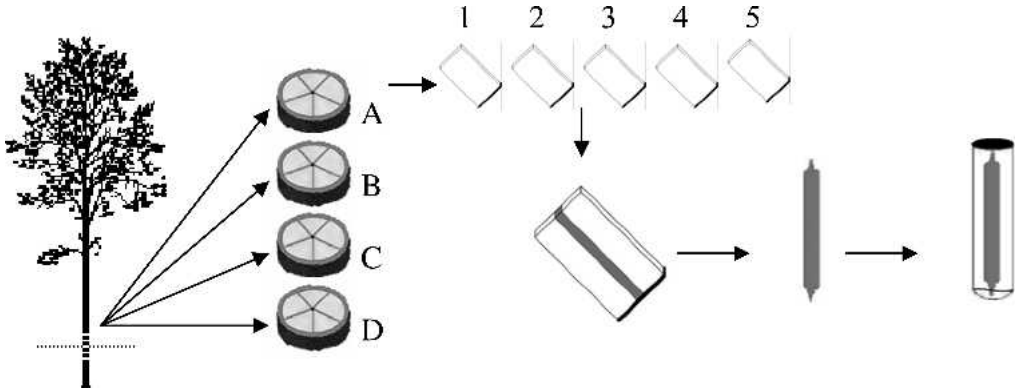

FIG. 1. Sampling of red alder trees and preparation of wood samples.

pressed using the CIE L*a*b* space system, which consists of three parameters: **L*** is lightness (0 = black; 100 = white), **a*** is greenness/redness (–60 = green; 60 = red), and **b*** is blueness/yellowness (–60 = blue; 60 = yellow) (Minolta 1998). According to Phelps et al. (1994), a difference of approximately three color units can be detected by the human eye. Yellowness and blueness were insignificant characteristics of color change in thermally modified red alder, and hence b* measurements are not presented or discussed in this paper.

Separate pith-to-bark samples were weighed, wrapped in foil, and heated, as above, at 20° (room temperature), 30°, 50°, 70°, and 90°C. The samples were removed from the test tubes periodically (after 8, 24, 36, 48, and 72 h) and reweighed. After 72 h, the samples were oven-dried at 105°C for 7 h and their moisture contents calculated.

In order to compare the color of samples subjected to the different heat treatments with that of commercially produced veneer, the color of several red alder veneer sheets with the desired tan color was measured. The color of these veneers provided reference maxima and minima for L* and a* values obtained from the measurement of the color of samples from red alder trees (above), and are displayed as dashed lines on graphs depicting results of this study in Figs. 2–5. While these maxima and minima provide a general range of favorable color measurements, they were not mathematically derived, nor do they represent a color standard for the red alder veneer industry as a whole.

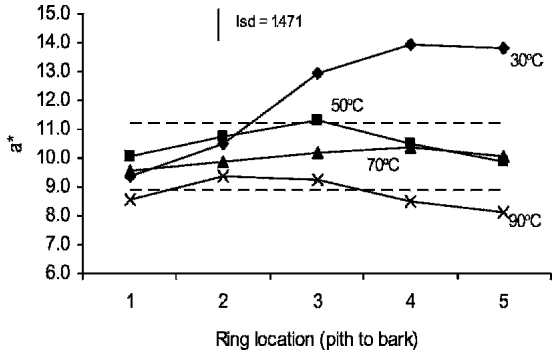

FIG. 2. Effects of temperature and ring location on a* (redness) of heated red alder wood.

Experimental design and statistical analysis

This experiment used factorial principles to determine the effects of three fixed factors (treatment temperature, heating time, and ring location) on two response variables (L* (lightness) and a* (redness)). Random effects arise because of between- and within-tree variation in wood properties, and elapsed time between replicate measures. Analysis of variance was used to examine fixed and random effects on the response variables. Statistical computation was performed using Genstat 5, using a p-value of 0.05 (5%) (Lawes Agricultural Trust 1994). Before the final analysis, diagnostic checks were performed to determine whether data conformed to the underlying assumptions of analysis of variance, i.e., normality with constant variance. Significant results ($p < 0.05$) are presented graphically and least significant difference (lsd) bars are used to compare differences between means.

RESULTS

There were significant effects of temperature, heating time, and ring location on L* (lightness) and a* (redness) (Table 1). There were also significant two-way interactions of temperature and heating time on a* and temperature and ring location on L* and a* (Table 1).

The overall effect of increasing temperature during the thermal modification of red alder wood was to make samples slightly less red (a* decreased) and darken them (L* decreased) (Figs. 2 and 3, respectively). Differences in the lightness and redness of samples heated at 70° and 90°C were small and generally statistically insignificant. The effect of temperature on the color of the wood, however, depended on the location of the sample within the tree, as indicated by the significant temperature × ring location interaction in Table 1. Wood samples cut adjacent to the bark developed a more pronounced orange/red color when heated at 30°C

TABLE 1. *Significant effects of, and interactions between, treatment temperature, heating time, and ring location on L* and a* color parameters.*

	Fixed Factors						
Response variables	Temperature (T)	Heating time (H)	Ring Location (R)	T × H	T × R	H × R	T × H × R
L*-lightness	***	***	***	NS	***	NS	NS
a*-redness	***	***	***	***	***	NS	NS

*** = $p < 0.001$; NS = not significant ($p > 0.05$)

than samples cut close to the pith. This observation is reflected by the relatively high a* values and lower L* values for the relevant samples (3 to 5) in Figs. 2 and 3. In contrast, the effect of ring location on the color of samples heated at 50°, 70° and 90°C was smaller. Within-tree differences in the color of thermally modified samples were least pronounced for those heated at 70°C, and the color of these samples all fell within the preferred color limits for red alder veneer.

If results in Figs. 2 and 3 are compared, it can be seen that there were marked differences in the pith-to-bark variation in redness and lightness of red alder wood following thermal modification at different temperatures. Differences in the redness of wood close to the pith (samples 1 and 2) were small irrespective of heating temperature, including samples heated at 30°C. As mentioned above, wood close to the bark was redder and darker when heated at 30°C, but differences in the redness of samples heated at 50°, 70° and 90°C were small, irrespective of their location in the tree stem. In contrast, there were significant differences in the lightness of wood heated at higher temperatures (70° and 90°C) compared to those heated at lower temperatures (30° and 50°C), particularly for wood close to the pith. Samples heated at 70°C were darker than those heated at 90°C, but the differences were not statistically significant.

Figure 4 shows the effect of heating time on the L* value for thermally modified samples. Results in this figure are averaged across temperature and ring number as there were no significant interactions of heating time with temperature or ring location (Table 1). Wood samples became darker as the length of time that they were exposed to heat increased. Thus, L* decreased from 73.90 for samples heated for 8 h to 67.18 for samples heated for 72 h. Heating times of 24 to 72 h produced values for L* that fell within industry preferences.

The effect of heating time on the redness of samples depended on temperature as indicated by the significant temperature × heating time interaction in Table 1. This occurred because there was a pronounced increase in the redness of samples heated at 30°C over the first 36 h followed by a pronounced decrease over the following 36 h, whereas there was little change over time in the redness of samples heated at higher temperatures (with the exception of

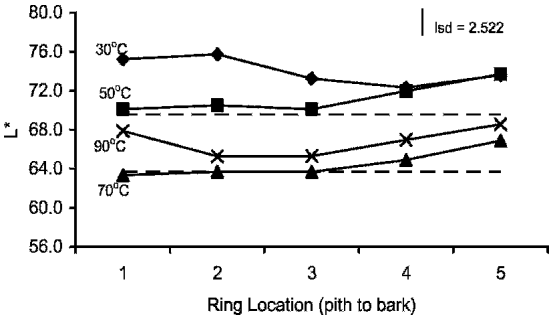

FIG. 3. Effects of temperature and ring location on L* (lightness) of heated red alder wood.

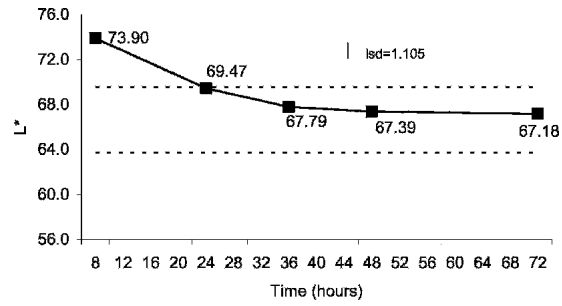

FIG. 4. Effects of heating time on L* (lightness) of red alder wood.

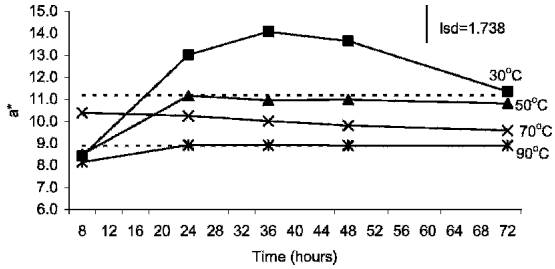

FIG. 5. Effects of temperature and heating time on a* (redness) of red alder wood.

samples heated at 50°C from 8 to 24 h) (Fig. 5). The redness of samples heated at 70°C remained consistent irrespective of heating time and fell within industry preferences. Heating times of 24 to 72 h seemed to produce the color that industry prefers. Measurement of the moisture content of separate pith-to-bark samples heated at different temperatures showed a decrease in their moisture contents over time. Decreases in moisture content were pronounced at the higher (70° and 90°C) temperatures (Table 2).

DISCUSSION

From first principles, it can be assumed that the color of thermally modified red alder wood results from the production and/or destruction of chromophoric groups. It is well known that red alder wood changes from a cream to a red/orange color on exposure to air (Simpson 1991). This color change occurs at ambient temperatures, and is probably caused by Maillard reactions between sugars and amino acids/proteins in wood (Kapp et al. 2003; McDonald et al. 2000). The production of new chromophores as a result of these reactions may explain our finding that wood close to the bark, where concentrations of sugars are likely to be high, was much redder than wood close to the pith when wood samples were heated at 30°C. It is also well established that hemicelluloses are degraded by heat, causing thermally modified wood to be darker than unmodified wood (White and Dietenberger 2001). Thermal degradation of wood may explain why red alder wood heated at higher temperatures (70° or 90°C) was darker than wood heated at 30° or 50°C, and the positive correlation between heating time and darkening of wood. Wood heated at 70°C, however, was darker than wood heated at 90°C, and wood close to the bark and heated at 30°C was as dark as wood heated at 50°C. The latter observation suggests that the red color (a*), which was pronounced in the outer wood heated at 30°C, contributed to the darkness (decreased L*) of thermally modified red alder wood. Accordingly, samples heated at 90°C were lighter than those heated at 70°C, possibly because of their lower redness. This suggestion is supported by results showing that wood heated at 70°C was redder than wood heated at 90°C, and the association between decreased redness and reduced darkening in wood samples heated at 70° and 90°C (compare Figs. 2 and 3). This negative correlation between redness of samples and heating temperature could result from inhibition of the (Maillard) reactions that produce the orange/red color in red alder wood and/or the destruction of the complexes responsible for the color. We consider the latter more likely since samples subjected to prolonged (72 h) heating at 30°C were less red than samples heated for shorter periods of time at the same temperature. This suggests that the orange/red complexes produced in red alder are thermolabile, and hence

TABLE 2. *Moisture content of pith to bark samples heated at different temperatures.*

	Heating time (hours)					
Temperature °C	0	8	24	36	48	72
20	98.5	96.1	94.4	92.1	88.1	83.1
30	102.3	99.8	97.9	95.4	92.4	88.4
50	126.8	119.2	103.5	96.3	84.7	69.3
70	105.7	84.2	60.8	50.7	31.1	15.1
90	95.0	61.7	16.2	6.7	1.8	1.2

are degraded by prolonged exposure to heat and higher temperatures.

Clearly, the thermal modification of color in red alder involves a complex suite of reactions. Our findings suggest that the final color of the wood depends on the strength of reactions that produce orange/red chromophoric groups in the wood, thermal darkening of the wood, and destruction of orange/red chromophoric groups. Therefore, the key to controlling color in veneer cants during steaming may lie in balancing these competing reactions through careful control of heating temperatures and times, and wood moisture content. Color control is complicated by within-tree and, possibly, seasonal variation in the strength of the reactions that generate the orange/red chromophores in wood and thermal and moisture gradients within veneer cants during steaming. A more complete understanding of these sources of variation through research on the thermal modification of larger samples would assist efforts to obtain better color uniformity in veneer sliced sequentially from heated veneer cants. Nevertheless, our findings on small samples indicate that heating red alder wood at 70°C for 24 to 36 h can produce the preferred tan color for this species. Higher temperatures in the outer layers of veneer cants may compensate for the tendency of outer wood to become redder by destroying red/orange chromophores and this may produce more uniformly colored veneer. Large thermal gradients from the outer to the inner wood, however, are likely to produce the pronounced differences in the color of veneer sheets that industry currently observes. A technology capable of more evenly heating veneer cants, possibly involving a combination of steaming and radio-frequency heating, might reduce the extent of such gradients and color variation in red alder veneer. Direct thermal modification of veneer might achieve a similar effect, although higher temperatures would be needed to accelerate color changes.

CONCLUSIONS

1. There is variation in the color of red alder wood samples cut sequentially from the pith to the bark and subjected to heating under isothermal conditions, but differences are pronounced only when wood is heated at 30°C. Wood close to the bark tends to be redder than wood close to the pith when heated at low temperatures, but such a difference is absent in wood heated at higher temperatures (50°–90°C).
2. Heating small pith-to-bark red alder wood samples at 70°C for 36 h produced wood that had an even tan color from pith to bark and fell within the current industry color preferences.
3. It is hypothesized that the color of thermally modified red alder wood depends on the strength of reactions that produce orange/red chromophores in the wood, thermal darkening of the wood, and destruction of orange/red chromophores. The key to controlling color in veneer cants during steaming lies in balancing these competing reactions through careful control of heating temperatures and times.
4. A better understanding of reactions that generate the orange/red chromophores in red alder wood and the magnitude of thermal gradients within veneer cants during steaming would assist efforts to obtain better color uniformity in veneer sliced sequentially from heated veneer cants.

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