VARIATION OF CELL FEATURES AND CHEMICAL COMPOSITION IN SPRUCE CONSISTING OF OPPOSITE, NORMAL, AND COMPRESSION WOOD

Asghar Tarmian[a*] and Mohammad Azadfallah[a]

A number of important anatomical features and chemical composition in opposite, normal, and compression wood of Norway spruce (*Picea abies)* were evaluated to optimally utilize spruce logs containing compression wood. A comparison of axial tracheid and ray cell features in the opposite, normal, and compression wood was provided. Lignin, cellulose, acetone-soluble, and water-soluble extractive contents of the woods were also determined. Results revealed a major variation in the anatomical and chemical characteristics of the woods. Compression wood showed extremely different microscopic features, and chemical composition compared to normal and opposite wood. In most of features investigated in the present study, normal wood occupied a transitional position between opposite and compression wood.

Keywords: Cell features; Chemical composition; Compression wood; Normal wood; Norway spruce; Opposite wood

*Contact information: a: Department of Wood Science and Technology, Faculty of Natural Resources, University of Tehran, Karaj, Iran, P.O.BOX 31585-4314, Tel: (98) 261 222 30 44, Fax: (98) 261 222 30 44; *Corresponding author: tarmian@ut.ac.ir*

INTRODUCTION

Norway spruce, which is used commonly in different practical purposes of wood, usually suffers compression wood formation. Compression wood is an abnormal woody tissue that typically develops in fast-growing trees on the lower side of leaning trees or the underside of branches (Timell 1986). It is a gravitational response, and its formation tends either to return a leaning stem to an upright position or to maintain the position of a branch within the crown (Burgert et al. 2004). Harris (1977) reported that compression wood occupied up to 20% of log volume in *Pinus radiata* trees in New Zealand forest. Several authors also have demonstrated the formation of compression wood in apparently vertical trees (Donaldson et al. 2004; Tarmian et al. 2008). Ladell et al. (1968) estimated the severity of compression wood formation in 20 mature trees of black spruce (*Picea mariana*) on a good site in Parnell Township, Ontario. They found that even in the good site, the mean compression wood content in 11 trees was 13.9 percent by volume, with mean values in individual trees varying from 5.3 to 26.1 percent. Thus, compression wood is expected to currently occur in Norway spruce logs, and then affect the wood properties.

In a spruce log containing compression wood, three different wood types can be separated: opposite, normal, and compression wood. Botanically, the area opposite to the compression wood (CW) region is termed "opposite wood" (OW) (Timell 1986). Normal wood (NW) is also defined as wood from growth rings that do not contain any compression wood (Donaldson et al. 2004). The abnormal properties of compression wood make it an undesirable feature for commercial lumber (Timell 1986), wood-based panels (Akbulut et al. 2006), and pulp and paper manufacture (Ban et al. 2004). Thus, the detection of compression wood in a green lumber would be useful to efficiently organize its application. Nyström and Kline (2000) used a color camera and an X-ray scanner to detect compression wood in green southern yellow pine. In contrast to X-ray scanning, color information was found to be useful in detecting compression wood.

Compression wood differs from normal and opposite woods with respect to chemical and anatomical properties (Singh et al. 2003; Yeh et al. 2005; Yoshizawa and Idei 1987; Singh and Donaldson 1999; Donaldson et al. 2004). It contains shorter and rounder tracheids of thicker walls and larger intercellular spaces when compared to normal wood (Donaldson et al. 2004; Burgert et al. 2004). Kienholz (1930) reported a greater radial diameter in the tracheids of compression wood in *Tsuga mertensiana*, whereas Donaldson et al. (2004) found slightly less radial diameter of tracheids in compression wood of radiata pine compared to opposite wood. Doerksen and Mitchell (1965) observed only slight differences in radial diameter of tracheids between normal and compression wood in the genus of *Abies*. Petric (1962) found that the tracheid cells of *Abies alba* in normal wood were longer than those of opposite wood. Downes et al. (1994) examined dimensions of tracheids in *P. radiata* for various wood types using a new wood microstructure analyzer. Donaldson et al. (2004) observed thicker tracheid cell walls in severe compression wood of radiata pine compared to opposite wood. In the case of ray cell features, Timell (1972) reported that the incidence and size of rays in compression wood were similar to those in normal wood except for *Pinus resinosa*, where rays were more numerous and larger in compression wood. Most of studies as mentioned previously were conducted to compare microscopic features of compression wood with those of opposite wood or those between opposite and normal wood, and there is no comparative information available especially on ray cell features of opposite, normal, and compression wood together in *Picea abies*.

Regarding chemical composition, it is well known that compression wood contains less cellulose and more lignin and hemicelluloses than normal wood (Lohrasebi et al. 1999; Onnerud 2003; Yeh et al. 2005). Compression wood lignin has a higher proportion of *p*-hydroxyphenyl units and a higher frequency of condensed structures than normal wood (Adler 1977; Timell 1986). Nimz et al. (1981) characterized the structural features of compression wood lignin in terms of guaiacyl, syringyl, and p-hydroxyphenyl units using ^{13}C-NMR spectroscopy. Timell (1973) reported that the opposite wood of *Picea mariana* had approximately the same lignin content as normal wood. Lohrasbei et al. (1999) found no significant difference in chemical properties of opposite and normal wood in black spruce, expect in alpha-cellulose and hemicellulose content. Despite major studies on chemical composition of compression wood, there has been a lack of information concerning the extractive content of compression wood in *Picea abies* as compared with opposite and normal wood.

The main objective of present study is to evaluate several important microscopic features and chemical composition of three different types of woods (opposite, normal and compression wood) in Norway spruce (*Picea abies*). The results presented here can be helpful to efficiently organize the application of spruce logs containing compression wood.

EXPERIMENTAL

Materials

Some trees of Norway spruce (*Picea abies*), about 16 years old, and growing in the north of Iran were freshly felled in the spring. In fact, the specimens that were characterized were juvenile wood of the species. Then, a number of logs consisting of major compression wood were selected for the study. Severe compression wood in the cross section of the logs was detected by the aide of its dark brown color. Subsequently, several disks containing opposite, normal, and compression wood (Fig. 1) were taken from the logs. To measure anatomical and chemical features, the blocks of 20 × 20 × 20 mm were cut for each wood.

Fig. 1. A disk of *Picea abies* consisting of compression wood (CW), normal wood (NW), and opposite wood (OW).

Methods

Microscopic features

The underside of disks where compression wood is formed consists of three different woody tissues: earlywood, latewood, and compression wood (Fig. 2). Thus, the anatomical features of only severe compression wood tissue, showing a circular cross section view of tracheids were studied. The features of tissues very close to the upper side of a compression wood zone were reported as those of normal wood (see also Fig. 1). In the upper side of disks where opposite wood is formed, the mean value of early- and latewood features within growth rings, corresponding to those of compression wood were reported. Microscopic preparation was made by using the usual methods of softening, sectioning, and mounting. Transverse, radial, and tangential sections of 20 to 30 µm thickness were cut using a sliding microtome, and subsequently the observation of microscopic features was made by the aid of a light microscope with an attached camera. The type, length, diameter, and proportion of ray cells were determined. For each wood, the total diameter, wall thickness and lumen diameter of axial tracheids were measured under the light microscope. The length of tracheid cells was measured by the Franklin method. The blocks were split into small pieces of matchstick size and were macerated by using a 50-50 V/V mixture of 60% acetic acid and 30% hydrogen peroxide in a test tube. After staining with safranin, the fibers were separated by shaking, and the length of isolated tracheids was measured under the light microscope. The mean of 30 measurements was taken in each property to be evaluated.

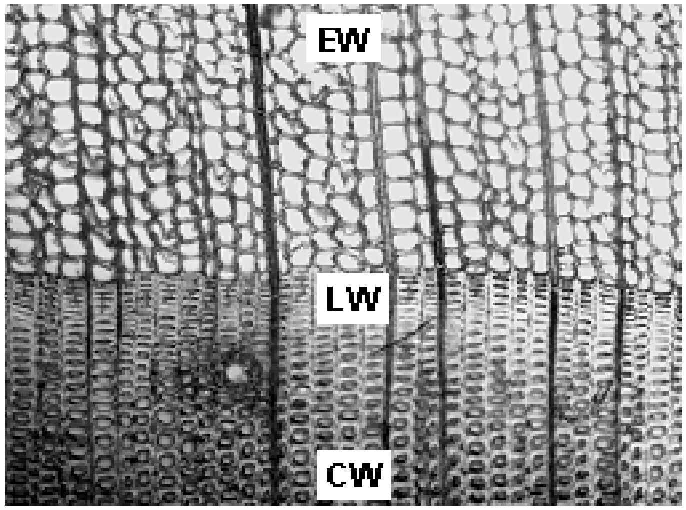

Fig. 2. Three different woody tissues in underside of disks, coloring dark brown: Earlywood (EW), latewood (LW), and compression wood (CW).

Chemical composition

All wood samples were air-dried and ground in Wiley mill to pass a 40 mesh screen. Then, prior to determining the cellulose and lignin content, wood flour was extracted with acetone overnight in a Soxhlet extractor. Lignin and cellulose contents of each wood were analyzed according to T 222 om-98 standard, and the Kurschner and Hoffer method, respectively. For each wood, acetone-soluble and water-soluble extractive contents were also determined based on TAPPI standard methods, T 280 pm-99 and T 207 cm-99, respectively.

RESULTS AND DISCUSSION

Microscopic Features

Results indicated a significant difference in cell dimension of opposite, normal, and compression woods. As illustrated in Fig. 3, total and lumen diameters of axial tracheids varied significantly among the woods. Opposite wood tracheids appeared to have larger total and lumen diameters compared to normal and compression wood. The average diameter of tracheids was 21.1, 25.5, and 28.9 µm respectively for compression, normal, and opposite wood. Lumen diameter was observed to be 11.9 µm for compression wood, 20.7 µm for normal wood, and 21.9 µm for opposite wood. This is in agreement with that for *radiata pine* (Donaldson et al. 2004) but it differs from that reported for *Tsuga mertensiana* (Kienholz 1930). Tracheids in both compression and normal woods were shorter than those in opposite wood (Fig. 4). The mean length of tracheids was 2.8, 3.4, and 2.2 mm respectively for normal, opposite, and compression wood. Much thicker tracheid walls were observed in compression wood compared to normal and opposite wood (Fig. 4). The mean wall thickness of tracheids was 2.4 µm for normal wood, about 3.5 µm for opposite wood, and 4.6 µm for compression wood. As shown in Fig. 5, the rectangular shape of tracheids on cross section changes to circular one from opposite wood (early- and latewood) to compression wood.

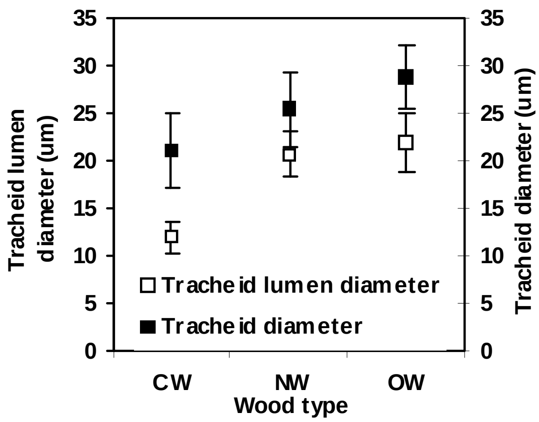

Fig. 3. Variation of total and lumen diameters of axial tracheids in compression, normal, and opposite wood (CW, NW, and OW).

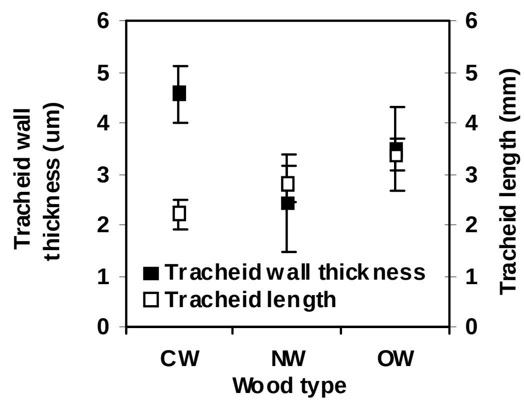

Fig. 4. Variation of length and wall thickness of axial tracheids in compression, normal and opposite wood (CW, NW, and OW).

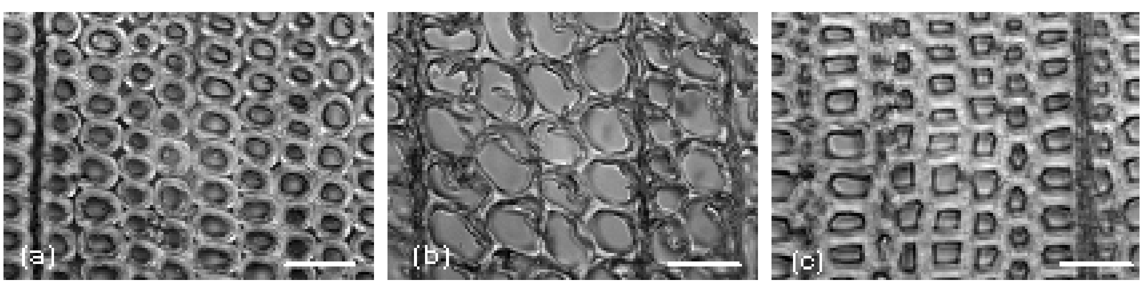

Fig. 5. Cross section views of longitudinal tracheids in compression wood (a): early-, (b): latewood, (c): of opposite wood. Scale bars: 50 µm.

Rays of compression wood were found to have larger height than those of opposite and normal wood (Fig. 6). The average height of uniseriate rays was 279.2 µm (mostly 9-13 cells) in compression wood, 223.6 µm (mostly 6-9 cells) in normal wood, and 250 µm (mostly 4-7 cells) in opposite wood. The mean value of fusiform ray height ranged from 275 to 413 µm for the woods. It was found to be 413.7 µm in compression wood, followed by normal wood with 287 µm and opposite wood, 275 µm. This difference in ray size may be caused by the different amount of substances transported and stored in the upper- and lower side of a leaning tree. However, some studies (Timell 1972; Sudo 1969) revealed no difference in ray size for compression and normal wood.

Ray frequency in compression wood was lower than that in opposite and normal wood, but there was no difference between opposite and normal wood (Fig. 7). The average number of rays per mm^2 was 36 (28-53) in compression wood, 47 (32-65) in normal wood, and 48 (32-65) in opposite wood. This result is supported by Onaka (1949), who found the frequency of the rays to be lower in compression wood than in normal wood of ten coniferous species. Our result also is in agreement with Ollinmaa (1959) who observed 40 rays per mm^2 in normal wood of *Picea abies*, compared to 34 in compression wood. In contrast to our finding, Cieslar (1896) and Jaccard (1915) found that rays were slightly more frequent in compression wood than in normal wood in *Abies alba*, *Picea abies*, and *sequoia sempervirens*. Sudo (1969), contrary to the mentioned researchers, reported no difference in ray frequency for normal and compression wood of *Picea montigena*. Higher ray frequency in compression wood was attributed to the greater availability of photosynthate on the compression wood side (Cieslar, 1896). However, no exact explanation can be given for the different observations.

As can be seen in Fig. 8, rays were one cell wide in all three woods, but the typical appearance of fusiform multiseriate ray cells was also observed in their structure. Indeed, multiseriate rays in all three woods were formed only when they contained resin channels. Compression wood contained slightly wider multiseriate and uniseriate rays than did normal and opposite wood (Fig. 9), but the rays in normal and opposite wood had a similar width. The average width of uniseriate rays was 15.1 µm in compression wood, 12.5 µm in normal wood, and 12.8 µm in opposite wood. The average width of multiseriate rays was 30.1, 28.9, and 28.8 µm respectively for compression, normal, and opposite wood.

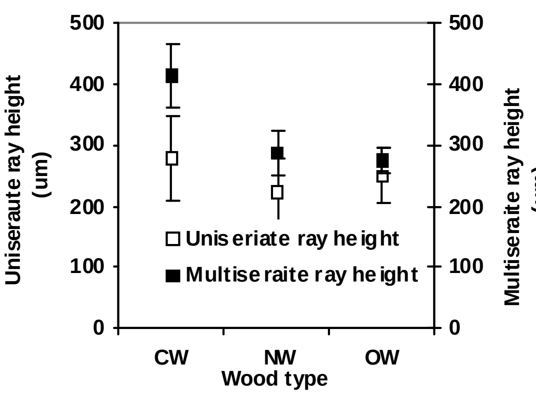

Fig. 6. Variation of uniseriate and multiseriate ray length in compression, normal wood and opposite wood (CW, NW, and OW).

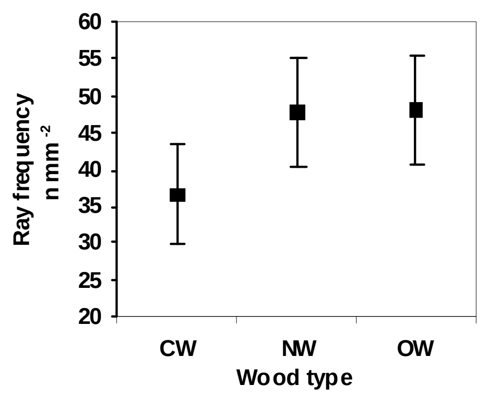

Fig. 7. Variation of ray proportion in compression, normal and opposite wood (CW, NW, and OW).

Chemical composition

Neither lignin nor cellulose content varied appreciably between normal and opposite wood, but compression wood had more lignin and less cellulose (Fig. 10). Such results have also been observed by other researchers (Lohrasebi et al. 1999; Timell 1986; Onnerud 2003; Yeh et al. 2005). Compression wood contained approximately 37% greater lignin and 43% lower cellulose than did normal and opposite wood.

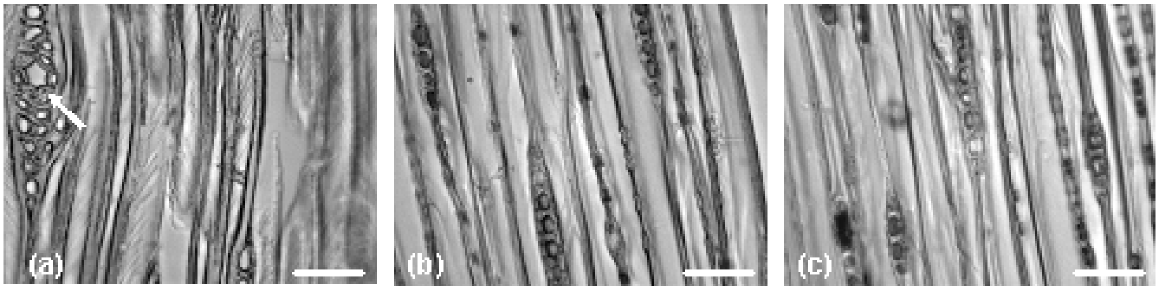

Fig. 8. Tangential section view of ray cells. (a) A multiseriate ray in compression wood; (b) uniseriate rays in opposite wood; (c) uniseriate rays in normal wood

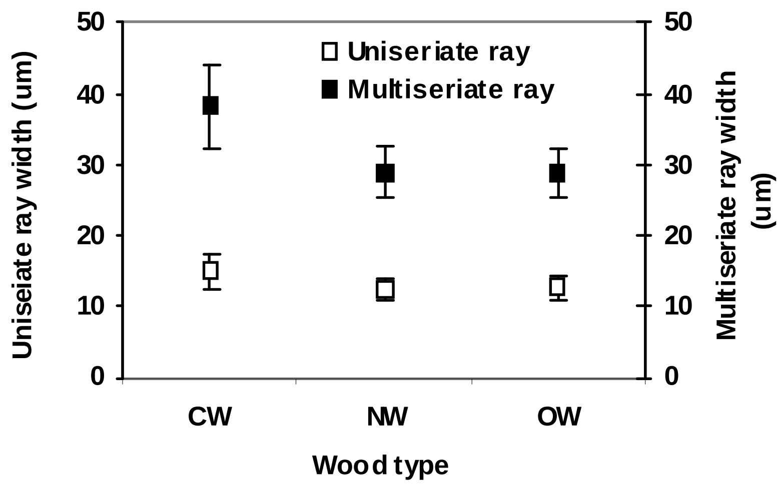

Fig. 9. Variation of width of uniseriate and multiseriate rays in compression, normal, and opposite wood (CW, NW, and OW).

These chemical characteristics of compression wood result in lower yield and a higher kappa number pulp and lower brightening response in comparison with normal and opposite woods (Mancosky et al. 2005; Wadenback et al. 2004). Since lignin structure and content can influence the distribution of preservative components in wood structure (Pizzi 1980; Pizzi et al. 1984; Ostmeyer et al. 1998), it can be inferred from our results that compression wood, due to the higher lignin content, has more potential to react with preservative components than normal and opposite wood. Since juvenile wood has higher lignin and lower holocellulose content compared to the mature wood (Guler et al., 2007), the results obtained here for spruce juvenile wood are likely to be different from those for its mature wood.

The high lignin content in compression wood can explain why it appears darker than normal wood. In fact, compression wood absorbs light more than normal wood. In addition, the dark color of compression wood is due to the thick wall of its tracheids as reported in the previous section, resulting less light scattering by compression wood compared to normal earlywood.

The results revealed little difference in water-soluble extractives content among compression, opposite, and normal woods. In contrast, compression wood showed lower acetone-soluble extractives than opposite and normal wood (Fig. 11). The acetone-soluble extractives averaged 1.1% for compression wood, 3.2% for normal wood, and 2.8% for opposite wood.

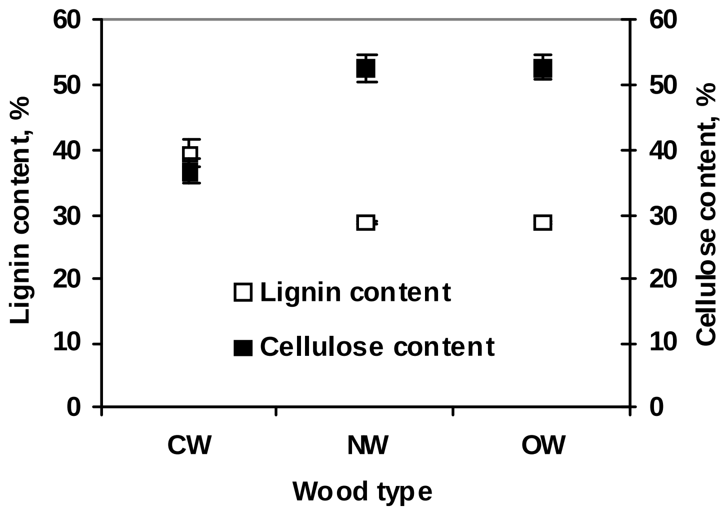

Fig. 10. Variation of lignin and cellulose content in compression, normal, and opposite wood (CW, NW, and OW).

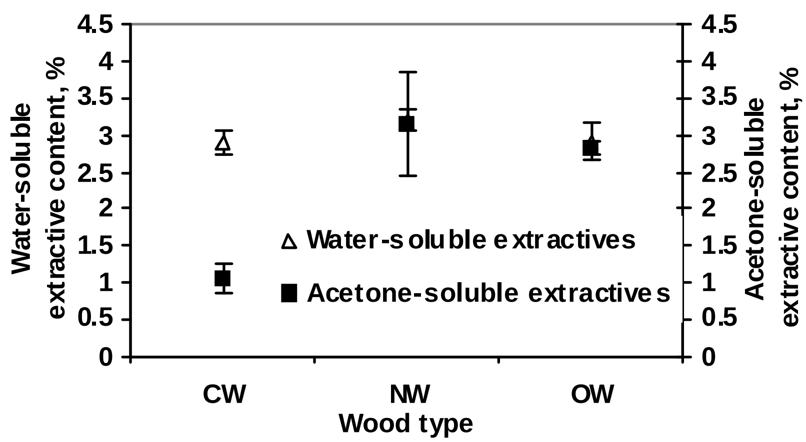

Fig. 11. Variation of water- and acetone-soluble extractive content in compression, normal, and opposite wood (CW, NW, and OW).

CONCLUSIONS

1. A significant difference between cell dimensions and chemical composition of compression wood and those of opposite and normal wood was observed for spruce juvenile wood.

2. More discrepancy between opposite and normal wood was found in axial tracheid features. Longer tracheids having wider lumens and thicker walls occurred in opposite wood.
3. Except for chemical composition, in many microscopic features studied here, normal wood occupied a transitional position between opposite and compression wood.
4. The characterized spruce wood here does not represent mature wood, but juvenile wood. Thus, further work is recommended to specify the anatomical and chemical features of compression, opposite, and normal wood in Norway spruce mature wood.

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