J. Korean Wood Sci. Technol. 42(5): 510~515, 2014 http://dx.doi.org/DOI : 10.5658/WOOD.2014.42.5.510

Anatomical and Physical Characteristics of Korean Paulownia (*Paulownia coreana*) Branch Wood[1]

Qi Yue[2] · Jae-Hyuk Jang[2] · Se-Hwi Park[2] · Nam-Hun Kim[2,†]

ABSTRACT

The anatomical and physical properties of tension wood (TW), opposite wood (OW) and lateral wood (LW) in the branches of Korean paulownia (*Paulownia coreana*) were compared. The diameter of TW vessels was larger than that of OW and LW vessels. The most distinctive feature of TW fibers was the presence of a gelatinous layer (G-fiber). The cell wall of TW fibers was nearly three times as thick as that of OW and LW. TW differed from OW and LW in density, X-ray diffraction pattern and shear and compressive strengths. The results obtained in this study showed clear differences in the anatomical and physical properties of TW, OW and LW of *Paulownia coreana* branch woods.

Keywords : branch wood, gelatinous fiber, lateral wood, opposite wood, *Paulownia coreana*, tension wood

1. INTRODUCTION

Trees respond to environmental influences and develop reaction wood to correct the posture of their leaning stems and branches. Reaction wood is formed in both hardwoods and softwoods; it is known as tension wood in hardwoods and compression wood in softwoods. In nature, in leaning stems, tension wood is formed on the upper side, while compression wood develops on the lower side (Wardrop 1964; Fisher and Stevenson 1981; Clair *et al*. 2006). The gelatinous layer (G-layer), a special fiber cell wall layer, is the most distinctive feature of tension wood (Lautner *et al*. 2012); this layer is highly crystalline. The compression wood typically has a higher density compared to normal wood. The outer region of the S2 layer in compression wood tracheids is highly lignified and tracheids are rounded (Timell 1986).

The secondary wall in normal wood fibers displays a three-layered structure, designated as S1, S2 and S3 layers. The tension wood is characterized by the presence of a special cell wall layers, gelatinous layer (G-layer), which occurs in following combinations of other cell wall layers: S1 + G, S1 + S2 + G, S1 + S2 + S3 + G (Wardrop and Dadswell 1955; Kwon 2008). The G-layer has high cellulose content and is unlignified or contains extremely low amounts of phenolic substances. The cellulose-rich tension wood could serve as an important source for nano-cellulose and also for pulp industries.

Tension wood has been examined for several spe-

1 Date Received May 1, 2014, Date Accepted June 11, 2014
2 College of Forest and Environmental Sciences, Kangwon National University, Chuncheon 200-701, Korea
† Corresponding author : Nam-Hun Kim (e-mail: kimnh@kangwon.ac.kr)

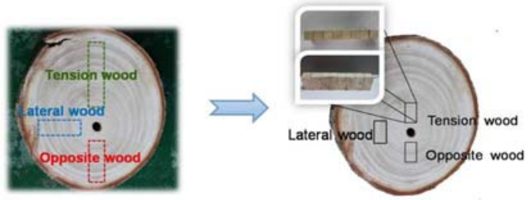

Fig. 1. Samples of *Paulownia coreana* branch wood.

cies such as Quercus mongolica (Lee *et al*. 1997), Subabul (Leucaena leucocephala) (Pramod *et al*. 2013) and some tropical rain forest wood species (Clair *et al*. 2006). However, there are only a few studies on the Korean native woods. In Korea, *Paulownia coreana* is a fast-growing tree species, the stems of which are extensively branched. Furthermore, the wood produced has value-added applications, such as in some Korean traditional musical instrument and furniture. However, with increasing use of trunks, branches are generally wasted. To evaluate the use of this branch wood resource from *Paulownia coreana* trees more efficiency, this study was undertaken to investigate its anatomical and physical characteristics.

2. MATERIALS and METHODS

2.1. Materials

Branch woods (13-year-old) of *Paulownia coreana* were obtained from the campus Forest (127.75°, 37.87°) of Kangwon National University in South Korea. Wood discs were collected from main limbs and categorized into TW, OW and LW as shown in Fig. 1.

2.2. Methods

2.2.1. Anatomical Characteristics

The samples containing tension wood (TW), opposite wood (OW) and lateral wood (LW) were obtained from wood discs. Fifteen μm-thick slices were cut in three different planes(transverse, radial longitudinal, tangential longitudinal) with a sliding microtome (Nippon Optical works, Japan). The sections were stained with Safranin-Astra blue (Von 1973; Lillie 1977; Jourez *et al*. 2001), dehydrated in a graded series of alcohol (50%, 70%, 90%, 95% and 99%), mounted in Canada balsam and observed with an optical microscope (Nikon Eclipse E600). The anatomical characteristics, such as number and diameter of vessels, height and width of rays, fiber length and structure, were determined according to the IAWA hardwood feature list (IAWA Committee 1989) using Total Imaging Solution (IMT, I-solution Lite). For each character, fifty random measurements were taken for each character to obtain a mean value.

2.2.2. X-Ray Diffraction

Relative crystallinity (Cr.) and crystallite width (τ) of TW, OW and LW were determined by an X-ray diffractometer (Rigaku DMAX2100V, Japan) and Segal's equation (Sequal *et al*. 1959) and Scherrer's (Alexander *et al*. 1969) equations.

2.2.3. Scanning Electron Microscopy

Samples with dimension of 5 × 5 × 5 mm^3 were prepared, air-dried, coated with gold using Gressington sputter coater (ULVAC G-50DA, Japan) and observed with a scanning electron microscope (JSM-5510, Japan).

2.2.4. Physical Characteristics

Small blocks for physical characters were prepared from TW, OW and LW of *Paulownia coreana* branch wood. Density (KS F 2198), shrinkage (KS F 2203), compression test parallel to grain (KS F 2206) and shear test (KS F 2209) measurements were carried out as per Korean standard (Korean standards association, 2004).

Table 1. Anatomical characteristics of tension wood (TW), opposite wood (OW) and lateral wood (LW) of *Paulownia coreana* branch wood

Characteristics		TW	OW	LW
Vessel elements				
Diameter (μm)	Tangential	195.7 ± 16	177.8 ± 17	166.4 ± 20
	Radial	239.3 ± 23	196.2 ± 21	195.2 ± 24
Cell wall thickness (μm)	Tangential	8.3 ± 1	2.6 ± 0.4	3.2 ± 0.5
	Radial	9.6 ± 2	3.5 ± 0.7	3.7 ± 0.5
Number per mm^2		10 ± 1	11 ± 2	10 ± 2
Fiber length (μm)		880.7 ± 77	748.8 ± 51	796.9 ± 81
Ray				
Height (μm)		258.6 ± 29	214.3 ± 23	210.2 ± 29
Width (μm)		46.4 ± 4	28.6 ± 2	28.7 ± 4
Number per mm^2		18 ± 1	20 ± 2	19 ± 1

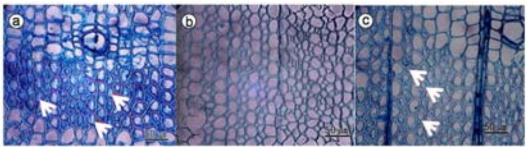

Fig. 2. Light micrographs of *Paulownia coreana* branch wood: a, tension wood (TW) with gelatinous fibers(following arrows); b, opposite wood (OW) without gelatinous fibers; c, lateral wood (LW) with small numbers of gelatinous fiber(following arrows).

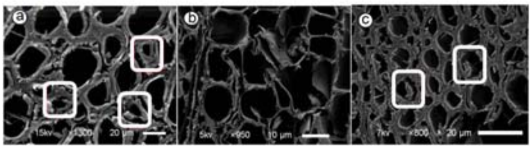

Fig. 3. SEM images of *Paulownia coreana* branch wood: a, tension wood (TW) with gelatinous fibers(rectangular box); b, opposite wood (OW) without gelatinous fibers; c, lateral wood (LW) with small numbers of gelatinous fiber(rectangular box).

3. RESULTS and DISCUSSION

3.1. Anatomical Characteristics

Anatomical characteristics of *Paulownia coreana* branch wood are summarized in Table 1. TW consisted of gelatinous fibers (Fig. 2a), with a gelatinous layer weakly attached to the inner secondary wall (Clair *et al*. 2006) (Fig. 3a). LW also contained G-fibers, but the number of G-fiber was fewer than that of TW. However, G-fibers were not present in OW (Fig. 2b, Fig. 3b). The cell wall in TW was approximately three times than that of OW. Vessel diameter of TW was much greater than in OW and LW in both tangential and radial directions. The width and height of rays in TW were greater than in OW and LW (Table 1). However, the numbers of vessel and ray per mm^2 did not show any noticeable variation among TW, OW and LW (Table 1). Fibers in TW were considerably longer than those in OW and LW, with values of 880.7 μm, 748.8 μm and 796.9 μm, respectively. The branch wood of *Paulownia coreana* appeared to differ from normal stem wood (Jeong *et al*. 2008), in the anatomical chaacteristics of vessel and ray elements.

3.2. X-ray Diffraction

The X-ray diffractograms of the samples are shown in Fig. 4, and crystalline properties of differ-

Table 2. Crystallite characteristics in TW, OW and LW of *Paulownia coreana* branch wood

Experimental parts	Crystallinity (%)	Crystallite width (nm)
TW	65.1	2.86
OW	60.7	2.71
LW	60.5	2.78

Table 3. Physical characteristics of tension wood (TW), opposite wood (OW) and lateral wood (LW) of *Paulownia coreana* branch wood

Characteristics		TW	OW	LW
Green density (g/cm^3)		0.70 ± 0.08	0.69 ± 0.08	0.62 ± 0.07
Oven-dry density (g/cm^3)		0.37 ± 0.06	0.36 ± 0.08	0.37 ± 0.08
Moisture content (%)		102.5 ± 10.7	94.3 ± 4.2	80.2 ± 17.4
Shrinkage	Tangential direction (%)	3.6 ± 0.1	5.3 ± 0.1	3.5 ± 0.1
	Radial direction (%)	1.8 ± 0.1	3.2 ± 0.1	2.5 ± 0.1
	T/R ratio	2 ± 0.28	1.6 ± 0.16	1.4 ± 0.48
Compressive strength (N/mm^2)		39.3 ± 5	47.8 ± 1	44.8 ± 5
Shear strength (N/mm^2)		12.7 ± 3	9.9 ± 2	9.1 ± 2

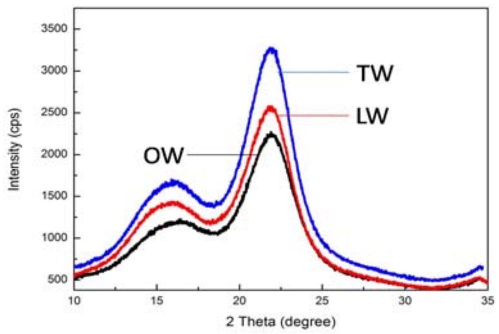

Fig. 4. X-Ray diffractograms of TW, OW and LW.

ent wood types of *Paulownia coreana* branch wood are summarized in Table 2. The relative crystallinity of TW was higher than that of OW and LW, and a corresponding trend was found with crystallite width. Generally, the cellulose crystallite width was larger in the G-layer than in the S2 layer, with diameter values were about 6.5 nm in G-layer and 3.1 nm in the S2 layer (Muller *et al*. 2006). Comparing with *Plantanus orientalis* (Lee and Kim 1993) and *Quercus mongoliaca* (Lee *et al*. 1997), the TW, OW and LW of *Paulownia coreana* branch wood showed a higher relative crystallinity.

3.3. Physical and Mechanical Characteristics

The data on the physical characteristics of TW, OW and LW of *Paulownia coreana* branch wood are prepared in Table 3, which show distinct differences among TW, OW and LW. The green density of TW and OW was higher than that of LW, while there were no large differences among them in the oven-dried density. Overall, green and oven-dry densities of branch wood were higher compared to stem wood, with recorded values of respectively, about 0.54 g/cm^3 and 0.22 g/cm^3 (Jeong *et al*. 2008). On the total shrinkage, the experimental values of OW were highest, with TW showing lower total shrinkage than OW and LW. The shrinkage of OW in branch wood was higher compared to normal stem wood, reported to be 1.38% and 4.16% in radial and tangential directions (Jeong *et al*. 2008). Furthermore, the density affects the coefficient of T/R ratio which becomes smaller with increasing density (Tsoumis 1991). Thus, the T/R ratio of branch wood was lower than that of normal stem wood. Density is one of the most important physical factors in the context of wood properties, and therefore the data on branch wood in our study provide important comparison with the recorded stem wood values.

With regard to mechanical characteristics, the shear strength of TW was higher than that of OW and LW (Table 3). However, the compressive strength of TW was lower than that of OW and LW (Table 3). The strength of wood is considered to increases with increasing density (Tsoumis, 1991). According to the data in our study, the compressive and shear strength of branch wood were much greater than those of normal stem wood, with recorded values of 15.19 N/mm^2 for compressive strength and 4.5-4.9 N/mm^2 for shear strength respectively (Jeong *et al*. 2008).

4. CONCLUSION

This study was carried out to investigate the anatomical and physical characteristics of branch wood of *Paulownia coreana* which is a fast-growing wood species. The observation showed TW contained abundant G-fibers and that LW also contained G-fibers but in smaller numbers. G-fibers were not present in OW. Fiber length, cell wall thickness, height and width of rays, relative crystallinity and shear strength in TW showed higher values than those in OW and LW. The green density of TW was similar to OW green density, but higher than that the green density of LW. However, the oven-dry density of TW, OW and LW were essentially similar. The results obtained in our study showed that the anatomical and physical properties of *Paulownia coreana* branch wood displayed some differences among TW, OW and LW. Branch wood is considered a low value wood, but this study provides information which can prove valuable in utilizing branch wood as an eco-friendly material in areas such as paper making, nanocellulose, food and cosmetics.

ACKNOWLEDGMENT

This study was carried out with the support from Kangwon National University in South Korea. Qi Yue also sincerely thanks the ACES-KNU scholarship of Kangwon National University for financial support from 2012.

REFERENCES

Alexander, L.E. 1969. X-ray diffraction in polymer science. Wiley-Interscience, Amsterdam. pp. 423～424.

Clair, B., Almeras T., Sugiyama, J. 2006. Compression stress in opposite wood of angiosperms: observations in chestnut, mani and poplar. Ann For Sci 63: 507～510.

Clair, B., Ruelle, J., Beauche^ne, J., Prevost, M.F., Fournier, M.. 2006. Tension wood and opposite wood in 21 tropical rainforest species about the presence of G-layer. IAWA J 27: 329～338.

Dadswell, H.E., Wardrop, A.B. 1949. What is reaction wood? Aust For 13: 22～33.

Dadswell, H.E., Wardrop, A.B. 1955. The structure and properties of tension wood. Holzforschung 9: 97～104.

Fisher, J.B., Stevenson, J.W. 1981. Occurrence of reaction wood in branches of dicotyledons and its role in tree architecture. Bot Gaz 142: 82～95.

IAWA Committee. 1989. IAWA List of microscopic features for hardwood identification. IAWA Bulletin n.s. 10(3): 219～332.

Jourez, B., Riboux, A., Leclercq, A. 2001. Anatomical characteristics of tension wood and opposite wood in young inclined stem of Poplar (Populus euramericana cv ‘Ghjoy’). IAWA J 22: 133～157.

Jeong, S.H., Park, B.S. 2008. Wood properties of the useful tree species grown in Korea. Korea Forest Research Institute 29: 348～368.

Korean standards association. 2004. KS F 2198, KS F 2203, KS F 2206 and KS F 2209.

Kwon M. 2008. Tension wood as a model system to explore to carbon partitioning between lignin and cellulose biosynthesis in woody plants. Journal of Applied Biological Chemistry 51(3): 83～87.

Lee, W.Y., Kim, N.H. 1993. Crystal structure of tension wood by x-ray diffraction method. Journal of Korean Wood Science and Technology 21(4): 65～73.

Lee, S.W., Hwang, W.J., Kim, N.H. 1997. Some anatomical characteristics in tension and opposite woods of Quercus mongolica Fischer. Journal of Korean Wood Science and Technology 25(3): 43～49.

Lillie, R.D. 1977. Conn’s Biological Stains. Williams and Wilkins Co., Baltimore.

Lautner, S., Zollfrank, C., Fromm, J. 2012. Microfibril angle distribution of poplar tension wood. IAWA J 33: 431～439.

Muller, M., Burghammer, M., Sugiyama, J. 2006. Direct investigation of the structural properties of tension wood cellulose microfibrils using microbeam X-ray fibre diffraction. Holzforschung 60: 474～479.

Segal, L., Creely, J.J., Martin, A.E., Conrad, C.M. 1959. An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer. Text Res J 29: 786～794.

Pramod, S., Rao, S.K., Sundberg, A. 2013. Structural, histochemical and chemical characterization of normal, tension and opposite wood of Subabul (Leucaena leucocephala (lam.) De wit.). Wood Science Technology 47: 777～796.

Timell, T.E. 1986. Compression wood in gymnosperms. Springer, Heidelberg.

Tsoumis, G.T. 1991. Science and technology of wood. Van Nostrand Reinhold, New York, 111～160.

Von Aufsess, B.H. 1973. Microscopic scope of lignification by staining methods. Holz Roh Werkst 31: 24～33.

Wardrop, A.B. 1964. The reaction anatomy of arborescent angiosperms. Academic press, New York London, 405～456.