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Original Article

Study on Red and Black Heartwood Properties of *Cryptomeria Japonica* in Southern Region of Korea[1]

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ABSTRACT

The heartwood (HW) of Japanese cedar (*Cryptomeria japonica*) has usually a reddish color. But some trees have black-colored heartwood (BHW). BHW of Japanese cedar has a low commercial value because of the appearance. Therefore, in this study, a comparative analysis was conducted to evaluate the differences in the physical, mechanical, and inorganic element properties, and decay resistance of red-colored heartwood tree (RHW) and BHW. The physical properties showed significant difference between sapwood (SW) and HW, but there was no significant difference between RHW and BHW. From the results of mechanical properties, no significant difference was recognized in SW of RHW, HW of RHW, SW of BHW, and HW of BHW. There were decay resistance differences between RHW and BHW in HW, and between HW and SW in both RHW and BHW, respectively. The magnesium (Mg), potassium (K), and calcium (Ca) contents had significant differences between SW and HW in both RHW and BHW. In this present study, the decay resistances and the contents of Mg and K were higher in HW than in SW both for RHW and BHW, while these measurements were lower in RHW than in BHW. Therefore, BHW was considered to be worthy as a high-quality material as RHW.

Keywords : *Cryptomeria japonica*, black-colored heartwood tree, physical properties, mechanical properties, decay, weight loss

1. INTRODUCTION

Global warming is an ongoing process and CO_2 is known as one of the biggest causes of global warming. Atmospheric CO_2 is inextricably linked to plant growth and thus directly affects the growth of the trees and forests (Sampson, 2014). As a result of recent global warming and climate change, evergreen tree species in warm temperate forest zones expanded their distribution extents (Jung *et al*., 2014). In this aspect, Japanese cedar (*Cryptomeria japonica*) is also one of those in Korea, and is likely to be recognized as more useful forest resources corresponding to climate change in warm temperate forest areas.

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Japanese cedar is one of the main tree species of southern coniferous forests and their plantations in Korea. Japanese cedar, commonly known as sugi, is a slender, pyramidal, and evergreen conifer. The tree grows to a height of 15 to 24 meters and a width of 6 to 9 meters; the large trees often reach a height of 30 to 38 meters. Japanese cedar heartwood usually becomes a red. Japanese cedar, which grows well in a warm climate, is a useful species for forest resources because global warming is an ongoing process. Japanese cedar also has many uses in the wood industry for its beautiful pattern and good lumber quality.

However, the biggest drawback of Japanese cedar is that its heartwood color sometimes varies from reddish to black. Japanese cedar with black-colored heartwood has a low commercial value because of the appearance. Genetic factors are believed to be the main reason for the emergence of different color in heartwood. However, all heartwood having similar genes do not show the same color. In other words, the color of heartwood can be different between individual trees even if they are within the same site environments (Sakagami *et al*., 2013). In addition, drying and transport costs of black-colored heartwood are required more than red-colored heartwood, this mainly caused by the differences of high green moisture content between individual trees (Kubo *et al.,* 1998).

In this aspect, research on low-priced black-colored heart wood of Japanese cedar is therefore necessary. Various studies have been conducted on black-colored heartwood of Japanese cedar. Kim *et al*. (2009) reported the material properties as a result of heat treatment, focusing on the color control by heat treatment. Matsunaga *et al*. (2006) clarified the differences in potassium distribution in the tissues of black-colored heartwood in terms of its anatomical morphology by using scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDXA) and optical microscopy. Takahashi (1996) studied the coloration of norlignans using alkaline treatment to clarify the relationship between the blackening and the presence of norlignans in the heartwood. Park *et al*. (2010) compared the green moisture content, mechanical properties of wood, and occurrence rate and causes of black-colored heartwood tree formation between two locations; in a general mountain forest and a windbreak forest for a mandarin orange field in Jeju island.

In this study, we focus on the evaluation of the physical, mechanical, and inorganic element properties and decay resistance of red-colored heartwood and black-colored heartwood, respectively obtained from *Cryptomeria japonica* stands in order to identify their potential applications as wood resources.

2. MATERIALS and METHODS

2.1. Materials

Japanese cedar (*Cryptomeria japonica* (Thund. ex L.F.) *D.Don*) trees grown in Gyeongnam (Namhae, Geoje), Jeonnam (Suncheon), and Jeju (Seogwipo) in southern

Table 1. Plot data of Japanese cedar obtained by stand survey

Classification		DBH (cm)	Height (m)	Stand age (year)	Elevation (m)	Latitude (DMS)	Stem number per ha (count)	BHW occurrence (%)*
Gyeongnam	Plot 1 (Namhae)	23.53 (5.23)	17.72	48	100-200	34°47′ N	1250	12% (6/50)
	Plot 2 (Geoje)	18.33 (6.45)	18.88	37	100-200	34°49′ N	2750	8% (4/50)
Jeonnam	Plot 3 (Suncheon)	32.22 (9.44)	19.05	46	500-600	34°54′ N	572	7.14% (2/28)
	Plot 4 (Suncheon)	34.92 (9.35)	20.15	35	500-600	34°54′ N	725	3.57% (1/28)
Jeju	Plot 5 (Seogwipo)	28.79 (9.98)	18.09	41	400-500	33°20′ N	750	10% (3/30)
	Plot 6 (Seogwipo)	28.7 (9.14)	19.13	47	400-500	33°20′ N	750	10% (3/30)
	Plot 7 (Seogwipo)	25.79 (5.25)	15.81	40	300-400	33°20′ N	700	10.71% (3/28)

DBH = diameter at breast height; BHW = black-colored heartwood tree; and *means the number of black-colored heartwood trees / the total number of Japanese cedar trees per fixed area.

Korea were used (Table 1). The sample tree selections for black-colored heartwood (BHW) red-colored heartwood tree (RHW) were conducted by examining color of cores obtained by increment borer in advance of felling trees. The heartwoods (HW) were grouped into two types by naked eye; BHW and RHW (Fig. 1). The total number of selected sample trees both for RHW and BHW were eight, respectively. Each RHW and BHW was felled within the same plot. The sample trees were felled one or two trees from seven plots. The trees dried in a natural room temperature condition were used later. The occurrence ratio of BHW in Japanese cedar stands was measured by increment cores and the occurrence ratio was randomly estimated per fixed area.


RHW BHW

Fig. 1. Classification of RHW and BHW.

2.2. Physical Properties Measurement

Shrinkage test (Air-dried shrinkage and oven dry shrinkage) was conducted in a constant temperature and humidity room (temperature 20 ± 2℃, relative humidity 65 ± 3%) according to the KS F 2203 in KS. The sample size was 20 × 20 × 20 mm. The number of samples of sapwood (SW) and heartwood (HW) were 10 per each tree, respectively. Specific gravity, annual ring width, and latewood ratio were measured using by the specimens of strength test according to KS F 2198 and KS F 2202.

2.3. Mechanical Properties Measurement

Bending test was performed on the samples using a universal testing machine (UTM) (TSU-2, Taeshin Accuracy Machine, Korea) with a center point loading method (concentrated load at mid span and supported at the ends). The size of sample was 20 × 20 × 320 mm and the span was 280 mm and the crosshead speed was set at 2.5 mm/min. The number of samples of SW and HW were 10 per each tree, respectively. Both bending modulus of elasticity (MOEb) and bending modulus of rupture (MORb) were calculated from load-deflection curves.

A compressive and shear strength tests were carried out according to the procedure of a Korean standard (KS F2206, 2004., KS F2209, 2004) using a hydraulic testing machine (EHF-ED10-20L, Shimazu, Japan). The loading speed was set at 1 mm/min. The load-deformation data were analyzed to determine the compressive modulus of elasticity (MOEc), compressive modulus of rupture (MORc), and shear modulus of rupture (MORs).

2.4. Decay Resistance Test

Decay resistance test was conducted in accordance with the KS F 2213. The white rot fungi, *Fomitopsis palustris* was used to examine the decay resistance. The medium was sterilized for 30 min at 121℃ and cooled down before inoculation. The testing fungi were inoculated on the potato dextrose agar medium (Becton, Dickinson and Company sparks, MD 21152).

The observation of decay resistance was conducted and a photograph was taken every week after inoculation. After the decay resistance test, weight loss was measured in SW and HW both of RHW and BHW. The tests were conducted from 18 experiment replications for each sample divided by SW of RHW, HW of RHW, SW of BHW, and HW of BHW. Weight loss ratio (P_w) was calculated according to the equation (1):

$$P_w = \frac{W_1 - W_2}{W_1} \times 100(\%) \quad \cdots\cdots (1)$$

Where, W_1 is the weight of specimen before decay operation, W_2 is the weight of specimen after decay operation.

2.5. Analysis of Chemical Components

The contents of inorganic elements were analyzed with a pretreated acid specimen using an inductively coupled plasma optical emission spectrometer (ICP-OES, PerkinElmer Optima 5300DV) in the research center at Gyeongsang national university. The tests were conducted from 6 experiment replications for each sample divided by SW of RHW, HW of RHW, SW of BHW, and HW of BHW.

Table 2. Physical properties of Japanese cedar due to RHW and BHW

Classification		Latewood ratio (%)	Annual ring width (mm)	Specific gravity	Air dry shrinkage (%)			Oven dry shrinkage (%)		
					T	R	T/R	T	R	T/R
RHW	SW	18.12[a] ± 3.34	3.07[a] ± 0.79	0.30[a] ± 0.04	3.45[b] ± 0.34	1.51[b] ± 0.31	2.28	5.88[a] ± 0.61	3.05[b] ± 0.52	1.93
	HW	26.56[b] ± 5.83	4.46[b] ± 0.87	0.30[a] ± 0.04	3.09[a] ± 0.49	1.09[a] ± 0.29	2.83	5.87[a] ± 0.81	2.63[a] ± 0.49	2.23
BHW	SW	19.39[a] ± 4.30	3.16[a] ± 0.57	0.30[a] ± 0.03	3.46[b] ± 0.48	1.49[b] ± 0.25	2.32	5.95[a] ± 0.50	3.07[b] ± 0.49	1.94
	HW	28.96[c] ± 7.80	4.40[b] ± 1.25	0.31[a] ± 0.03	3.15[a] ± 0.45	1.22[a] ± 0.71	2.58	6.09[a] ± 0.67	2.74[a] ± 0.47	2.22
SL		**	**	ns	**	**		ns	**	

Values are presented as mean; ± standard deviation; [a, b and c] mean that the same letters are not significantly different at a p-value of 0.05 according to Duncan's new multiple range test; ** = $p < 0.05$; SL = significance level; ns = non significant; RHW = red-colored heartwood tree; BHW = black-colored heartwood tree; SW = sapwood; HW = heartwood; T = tangential direction; and R = radial direction.

3. RESULTS and DISCUSSION

3.1. Occurrence of BHW

The occurrence frequency of BHW trees in Japanese cedar stands of Gyeongnam, Jeonnam, and Jeju area were 10%, 5.36%, and 10.11%, respectively (Table 1). Site elevation order was Jeonnam > Gyeongnam > Jeju. This result indicates that the ratio of BHW occurrence appeared conversely to site elevation. Kubo and Ataka (1998) also reported that the BHW of Japanese cedar occurred frequently in trees from the lower site of a sloped plantation near a mountain stream.

3.2. Physical Properties due to RHW and BHW

Table 2 shows the average values of physical properties of Japanese cedar. Latewood ratios in the SW and HW of RHW, SW and HW of BHW were 18.12%, 26.56%, 19.39%, and 28.96%, respectively. The results indicated that latewood ratio was higher in HW than in SW for both RHW and BHW. There was no significant difference in latewood ratio between RHW and BHW.

Annual ring widths in SW and HW of RHW were 3.07 and 4.45 mm, respectively. Annual ring widths in SW and HW of BHW were 3.16 and 4.40 mm, respectively. The result indicated that annual ling width was wider in HW than in SW in both of RHW and BHW, and there was no significant difference between RHW and BHW. Specific gravity was not significantly different between SW and HW of both RHW and BHW. For air dry shrinkage both in tangential and radial directions, the shrinkage of SW appeared to be higher than that in the HW for both of RHW and BHW. There was a significant difference between the SW and HW for both of RHW and BHW. But there was no significant difference between RHW and BHW. For oven dry shrinkage in

Table 3. Mechanical properties of Japanese cedar due to RHW and BHW

Classification		Bending strength property		Compressive strength property		Shear strength	Moisture content (%)
		MORb (MPa)	MOEb (GPa)	MORc (MPa)	MOEc (GPa)	MORs (MPa)	
RHW	SW	48.48[a] ± 10.12	6.67[a] ± 2.46	26.98[a] ± 6.77	2.93[a] ± 0.68	7.60[a] ± 0.94	12.59[a] ± 0.19
	HW	52.35[b] ± 9.52	7.18[a] ± 2.32	27.48[a] ± 5.67	2.89[a] ± 0.60	6.65[c] ± 0.93	12.52[a] ± 0.10
BHW	SW	51.86[b] ± 6.87	6.90[a] ± 1.43	28.11[a] ± 4.17	2.99[a] ± 0.46	7.51[bc] ± 0.90	12.70[a] ± 0.12
	HW	54.44[b] ± 7.66	7.42[a] ± 2.02	29.04[a] ± 5.04	2.93[a] ± 0.58	7.26[b] ± 0.89	12.55[a] ± 0.29
SL		**	ns	ns	ns	**	ns

Values are presented as mean; ± standard deviation; [a, b and c] mean that the same letters are not significantly different at a p value of 0.05 according to Duncan's new multiple range test; ** = $p < 0.05$; SL = significance level; ns = non significant; RHW = red-colored heartwood tree; BHW = black-colored heartwood tree; SW = sapwood; HW = heartwood; MORb = bending modulus of rupture; MOEb = bending modulus of elasticity; MORc = compressive modulus of rupture; MOEc = compressive modulus of elasticity; and MORs = shear modulus of rupture.

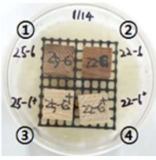
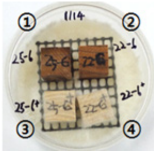
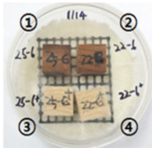
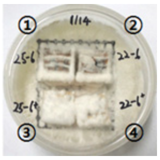
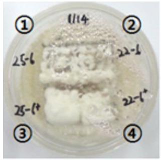
tangential direction, there were no significant differences among SW and HW of RHW, SW and HW of BHW. But there were significant differences between SW and HW of both RHW and BHW for oven dry shrinkage in radial direction. There were significant differences of physical properties in many factors between SW and HW of both RHW and BHW. There was no significant difference in physical properties between RHW and BHW. However, Yamashita *et al*. (2009) reported that Japanese cedar cultivars showed significant differences in tangential shrinkage, radial shrinkage, and tangential/radial shrinkage ratio within a stem and tangential/radial shrinkage ratio decreased with radius and height in the stems of most cultivars.

3.3. Mechanical Properties due to RHW and BHW

Table 3 shows the average values of mechanical properties. Bending MOR (MORb) in the SW and HW of RHW, SW and HW of BHW were 45.48, 52.35, 51.86, and 54.44 MPa, respectively. Bending MOE (MOEb) in the SW and HW of RHW, SW and HW of BHW were 6.67, 7.18, 6.90, and 7.42 GPa, respectively.

Compressive MOR (MORc) in SW and HW of RHW, SW and HW of BHW were 26.98, 27.48, 28.11, and 29.04 MPa, respectively. Compressive MOE (MOEc) were 2.93, 2.89, 2.99, and 2.93 GPa, respectively. Shear MOR (MORs) in were 7.60, 6.65, 7.51, and 7.26 MPa, respectively. In mechanical properties, there were no significant differences in MORb, MORc, and MOEc in SW of RHW, HW of RHW, SW of BHW, and HW of BHW. Also Matsunaga *et al*. (2006) reported that the strength properties of RHW were not significantly different from BHW.

Table 4. Decay properties of Japanese cedar due to RHW and BHW

Classification		Inoculation	1 week	2 week	4 week	8 week
RHW	SW③					
	HW①					
BHW	SW④					
	HW②					

Classification	RHW		BHW		SL
	SW	HW	SW	HW	
Weight loss (%)	50.03[c] ± 5.60	25.60[b] ± 12.10	46.59[c] ± 7.73	18.09[a] ± 8.39	**

Values are presented as mean; ± standard deviation; a, b and c mean that the same letters are not significantly different at a p value of 0.05 according to Duncan's new multiple range test; ** = $p < 0.05$; SL = significance level; RHW = red-colored heartwood tree; BHW = black-colored heartwood tree; SW = sapwood; HW = heartwood. ① = heartwood of RHW; ② = heartwood of BHW; ③ = SW of RHW; and ④ = SW of BHW.

3.4. Decay Resistance

Table 4 shows the decay resistance characteristics of Japanese cedar. From the results of naked-eye observation, the decay resistance were in order of HW of BHW > HW of RHW > SW of RHW = SW of BHW. The decay resistance indicated to be higher in HW than in SW for both of RHW and BHW.

Weight loss of SW and HW of RHW, SW and HW of BHW were 46.74%, 21.51%, 46.82%, and 16.57%, respectively. There were significant differences of weight loss between SW and HW both for RHW and BHW. Furthermore, there was a significant difference between HW of RHW and HW of BHW. From the results of decay resistance, decay resistance was significantly different in SW of RHW, HW of RHW, SW of BHW, and HW of BHW. The resistance to hyphae of BHW was higher than that of RHW. In addition to the resistance to fungi, Kurimoto (1998) reported that the results of the termite feeding tests showed resistance characteristics to be higher in HW than in SW of Japanese cedar.

3.5. Inorganic Element Properties

Table 5 shows inorganic elemental analytic results by ICP-OES of SW and HW of RHW, SW and HW of BHW. The contents of sodium (Na), calcium (Ca), magnesium (Mg), and potassium (K) in SW of RHW were 1.72, 7.70, 0.77, and 2.38 mg, respectively and 1.84, 5.58, 1.42, and 9.57 mg, respectively in HW of RHW. The contents of Na, Ca, Mg, and K showed 2.81, 7.88, 0.64, and 6.20 mg, respectively in SW of BHW and 2.04, 6.47, 1.91, and 17.37 mg in HW of BHW, respectively. The contents of Na, Ca, K, and Mg had statistically significant differences. The content of Ca had a tendency to be higher in SW than in HW for both of RHW and BHW. Mg and K contents had significant differences between SW

Table 5. Inorganic element properties of Japanese cedar due to RHW and BHW

Classification		Inorganic elements (mg/ℓ)			
		Na	Ca	Mg	K
RHW	SW	1.72^{a} ± 0.11	7.70^{b} ± 0.98	0.77^{a} ± 0.29	2.38^{a} ± 0.91
	HW	1.84^{a} ± 0.29	5.58^{a} ± 1.02	1.42^{b} ± 0.50	9.57^{c} ± 1.49
BHW	SW	2.81^{b} ± 0.19	7.88^{b} ± 0.80	0.64^{a} ± 0.10	6.20^{bc} ± 2.05
	HW	2.04^{a} ± 0.74	6.47^{ab} ± 2.01	1.91^{c} ± 0.51	17.37^{d} ± 8.69
SL		**	**	**	**

Values are presented as mean ± standard deviation; [a, b, c] means that the same letters are not significantly different at a p value of 0.05 according to Duncan's new multiple range test; ** = $p < 0.05$; SL = significance level; RHW = red-colored heartwood tree; BHW = black-colored heartwood tree; SW = sapwood; and HW = heartwood.

and HW both in RHW and BHW, and also had significant differences between RHW and BHW. The contents of Mg and K were greater in BHW than in RHW.

This fact that the total content of Ca, Mg, Na, and K was generally greater in BHW than in RHW was previously reported by many other researchers (Morikawaet *et al.*, 1996; Takahashi, 1996; Matsunaga *et al.*, 2006). However, Kubo *et al*. (1998) reported that high content for K only indicated among inorganic elements in BHW of Japanese cedar and the other inorganic elements had low value. The location of inorganic components in BHW of Japanese cedar was previously reported by the other researchers. Park *et al*. (2010) reported that the amounts of Mg and Kwere high in BHW of Japanese cedar, and inorganic elements of K_2O and CaO in the ray cells were thought to be one of the important factors for BHW formation of Japanese cedar. Additionally, Matsunaga *et al*. (2006) reported that K generally exists in tracheids, ray, and axial parenchyma cells in BHW. But the content of K in BHW of Japanese cedar is extraordinarily abundant in the axial parenchyma cells.

4. CONCLUSIONS

Most physical and mechanical properties of Japanese cedar mostly distributed in the southern area of korea showed no statistically significant differences between red-colored heartwood and black-colored heartwood of Japanese cedar trees distributed in Korea. The decay resistance and contents of magnesium and potassium were greater in black-colored heartwood tree than in red-colored heartwood tree. From our findings, with the lack of disadvantages in physical and mechanical properties, Japanese cedar with black-colored heartwood could be used as a more specific purpose and place even with an advantage of high resistant property to decay.

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