Microcrack Propagation in Red and Black Heartwoods of *Cryptomeria japonica* During Drying

Hiroki Sakagami,[a,]* Fumiko Hatae,[b] Hiroyuki Yamamoto,[b] Yoshio Kijidani,[c] and Junji Matsumura [a]

Microcrack behaviors in black and red heartwoods of *Cryptomeria japonica* were compared in this study. Black and red heartwoods have extremely different green moisture contents but similar wood structure. Small heartwood samples were prepared from these two types of green wood. Moisture contents of black and red heartwood were 201.5% and 51.3%, respectively. The samples were dried at 50 °C in a controlled-environment chamber with a relative humidity below 5%. The propagation of microcracks was continuously observed using a confocal laser scanning microscope while the samples dried. The electrical resistivity of the surface was also measured to assess surface moisture content. Results showed that the transformation of the microcracks was similar between black and red heartwoods. However, the appearance of microcracks in the black heartwood was delayed, whereas the microcracks appeared in red heartwood immediately after drying. These suggested that *in-situ* observation is essential for distinguishing when microcracks emerged. It was also suggested the green moisture content of heartwood has a major effect on the occurrence of microcracks. Drying conditions must be adjusted to account for the moisture content of green heartwood, even for specimens of the same species that have the same anatomical structure.

Keywords: Microcrack; Drying; Confocal laser scanning microscopy; Cryptomeria japonica; Red heartwood; Black heartwood

*Contact information: a: Division of Sustainable Bioresources Science, Faculty of Agriculture, Kyushu University 6-10-1 Hakozaki Higashiku Fukuoka, 812-8581, Japan; b: Graduate School of Bioresource and Bioenvironmental Sciences Kyushu University 6-10-1 Hakozaki Higashiku Fukuoka, 812-8581, Japan; c: Division of Forest Science, Faculty of Agriculture, Miyazaki University, Miyazaki, 889-2192, Japan; * Corresponding author: h-sakagami@agr.kyushu-u.ac.jp*

INTRODUCTION

Cryptomeria japonica D. Don is the most important plantation tree in Japan. There are many mature forests, and there is a growing interest in the development of methods for the effective utilization of *C. japonica* wood. However, there are several difficulties that must be overcome to utilize these trees. One problem is the cost of drying. The green moisture content (GMC) of this species differs widely within and between individual trees. Although the GMC of sapwood is fairly consistent at around 200%, that of heartwood ranges from 60 to 180% (Kawazumi *et al.* 1991). This large variation in the moisture content (MC) of heartwood is commonly found even among trees grown in the same area. Heartwood with a low MC is called red heartwood. Red heartwood has a reddish-pink color and is used extensively as a wood product. On the other hand, heartwood with a high MC is called black heartwood. Black heartwood has a black color immediately after felling. The black color of this heartwood has been attributed to the presence of potassium hydrogencarbonate (Abe and Oda 1994; Matsunaga *et al.* 2006; Takahashi 1996). Additionally, extractives in black heartwood are richer than red heartwood. Kawazumi *et al.* (1991) reported that there was significant correlation among the lightness, green moisture content, and extractives by hot water in heartwood. Genetic factor is believed to be the main reason for emergence of different color in heartwood. However, not every heartwood having similar genes shows the same color. In other words, the color of heartwood can be different between trees even if they have the same wood structure. Black-colored timbers are generally considered to be flawed, when *C. japonica* is used as materials, not only because of their dark color, but also because they require a long time to dry and it is expensive to do so.

Drying the heartwood of softwood is difficult because of its low permeability. Sano and Nakada (1998) described the encrusting materials in the pit membranes of heartwood. Fujii *et al.* (1997) reported that the encrustation of bordered pits in *C. japonica* heartwood disturbs air permeation. In addition, low permeability results in the formation of a large MC gradient between the surface and interior of the wood during drying. This moisture gradient contributes to the drying stress that causes cracks to appear on the surface of the wood. These cracks reduce the commercial value of the wood, therefore crack prevention during drying is very important for promotion of *C. japonica* use.

To reduce cracking in *C. japonica* during drying, many scientists have researched cracking generation and have suggested appropriate drying methods. Each method employs a different temperature, relative humidity, and drying schedule (Kuroda 2007). In general, these drying methods are assessed by measuring the residual cracking at the final stage of drying. Cracking, however, changes continuously during the drying process, and some cracking may have closed by the final stage of drying. Moreover, many microcracks that are invisible to the naked eye may exist, and the existence of such microcracks has been reported (Moren 1994; Perre 2003; Wahl *et al.* 2001; Hanhijärvi et al. 2003). These microcracks have the potential to propagate large-scale cracking, leading to degradation of wood quality. They are also considered to impact the strength because even cell wall damage at a microscopic level during drying may cause a decrease of tensile strength (Kifetew *et al.* 1998). Therefore, elucidating the mechanism of microcrack generation is essential for developing more suitable methods of drying.

To understand the process of microcrack formation, a confocal laser scanning microscopy (CLSM) system was devised that enables *in-situ* observation of wood surfaces during drying under the conditions of controlled temperature and relative humidity (Sakagami *et al.* 2007). Using this system, microcracks that developed during drying of the sapwood of *C. japonica* (Sakagami *et al.* 2009b), *Melia azedarach*, and an Acacia hybrid (Sakagami *et al.* 2009a) were visualized. These studies showed that microcracks were commonly generated in the ray parenchyma or adjacent to the ray parenchyma. However, in *C. japonica* and *M. azedarach*, which have distinct growth ring boundaries, microcracks appeared in the latewood region. In the Acacia hybrid, which does not have a clear growth ring boundary, the distribution of microcracks was not concentrated in a particular area. On the basis of these results, it has been assumed that the differences between species with respect to the morphological characteristics of microcracks depend on the wood structure. Furthermore, differences in MC between the surface and interior play an important role in microcrack generation and propagation. If the moisture condition of the wood surface is known when cracks occur, it may be possible to regulate drying conditions to control the moisture conditions in the wood and prevent or decrease the emergence of large cracks. To measure the MC of the wood surface, the CLSM system was modified to obtain information about the MC of the wood surface by measuring the electrical resistivity (Yamamoto *et al.* 2013). Using this modified system, it was shown that the electrical resistivity of the surface drastically changed when the microcracks emerged. The MC of the surface during drying could be also measured constantly.

Recent studies have indicated that the overall and surface MCs of the specimens and wood structure strongly affect the emergence and propagation of microcracks. In the present work, to determine the relationship between MC and wood structure, patterns of microcrack propagation in black and red heartwood of *C. japonica* were compared, as these types of hardwood have the same wood structure but differ widely in MC.

EXPERIMENTAL

Sample Preparation

Samples of red heartwood and black heartwood, both of the green softwood *C. japonica* D. Don, were prepared. Representative images of black and red heartwood which were not used in this study are shown in Fig. 1. Two trees containing red heartwood were cut down in a private forest in the Fukuoka prefecture, Japan. Two trees containing black heartwood were cut down in a private forest in the Kumamoto prefecture, Japan. An example of GMC variation from pith to bark in black heartwood is shown in Fig. 2. In the black heartwood trees, the heartwood and sapwood both had high GMC (~200%) relative to that of intermediate wood. From the black heartwood of the felled trees, specimen pairs consisting of two successive longitudinal specimens of 15 (R) × 15 (T) × 8 (L) mm were cut. The growth-ring boundary was positioned either parallel or perpendicular to the surface. One specimen from each pair was used for CLSM observation, and the other was used for MC measurement. The transverse surface was smoothed using a sliding microtome. Twelve pairs of red heartwood samples and 10 pairs of black heartwood samples were prepared. The average GMCs of these samples were 51.3% and 201.5%, respectively.

Fig. 1. Example image of red and black heartwood of *C. japonica*;
Left: red heartwood, Right: black heartwood

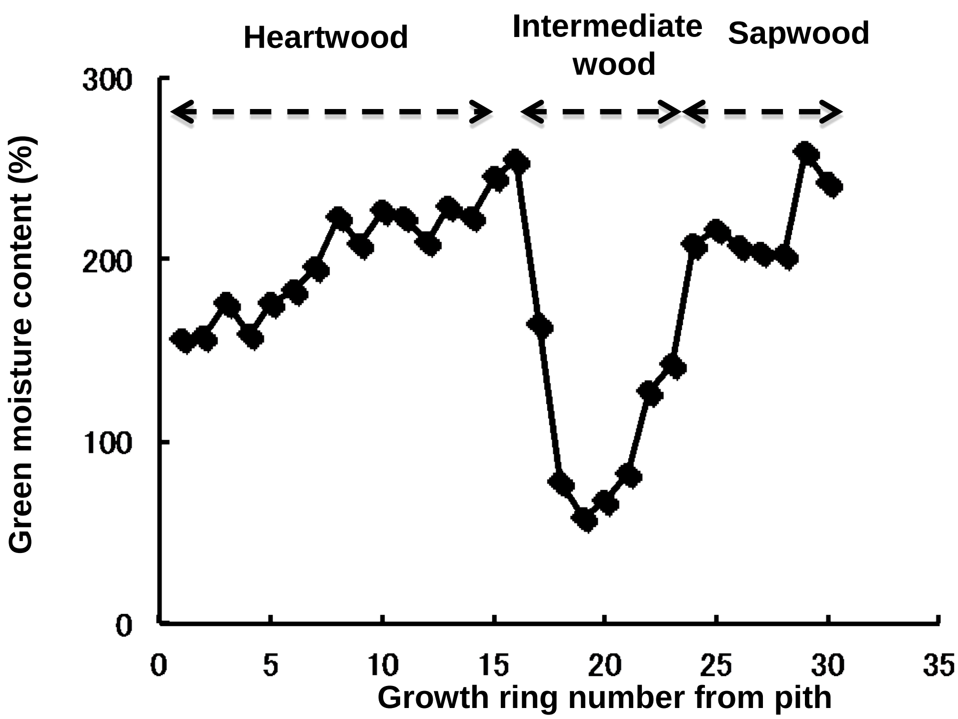

Fig. 2. Green moisture content of *Cryptomeria japonica* black heartwood from pith to bark; the moisture contents of heartwood and sapwood were high in comparison to that of intermediate wood.

Visualization and Drying Method

A CLSM system was used to visualize the occurrence of microcracks. This system, developed by Yamamoto *et al.* (2013), consists of a controlled-environment chamber equipped with a confocal laser scanning microscope (BIO-RAD Radiance 2000) and an electrical resistivity meter (Hiresta-UP MCP-HT450 Mitsubishi Chemical Analytech Co., Ltd.). This system enables the acquisition of high-quality images of the wood surface at the appropriate temperature and relative humidity and under atmospheric pressure. Environmental conditions were maintained using a humidity generator and thermolamps. A small fan was also placed inside the chamber to equalize atmosphere. Each pair of samples was placed on the CLSM stage and dried at 50 °C and at a relative humidity below 5% until the weight became fixed. Images of the wood surface were recorded using an argon ion laser with an excitation wavelength of 488 nm. Each initial image was taken after the pair of samples was placed on the stage, and successive images of the surface were captured until the wood was dry.

Measurement of Moisture Content

A steep MC gradient from the surface to the interior of wood is necessary for generating microcracks. This gradient is assumed to influence the morphology of microcrack generation. However, it is difficult to measure the MC of the surface and interior separately. To determine the relationship between the surface and interior MCs, two types of MC measurement were employed. One method was a conventional method and involved weighing the specimens. One specimen in each pair of samples was weighed at 15-min intervals during drying. The MCs were calculated from the weight of the oven-dried sample at the end of the experiment. The other method involved measuring the electrical resistivity. The conductivity of a direct electric current is associated with MC below the fiber saturation point. A resistivity meter (Hiresta UP Model MCP-HT450; Mitsubishi Chemical Analytech Co., LTD) was previously used to measure the electrical resistivity of wood surfaces (Yamamoto *et al.* 2013). The surface MC was then determined using two types of prepared regression equations (below and above 8% MC) (Fig. 3). The regression equations were derived from measurements of the surface electrical resistivity of red and black heartwood, adjusted to the equilibrium moisture content in several types of atmospheres in which the temperature was 50 °C and the relative humidity was controlled in desiccators filled with 5, 20, 80, or 100% saturated solutions of glycerin (resulting in RHs of > 90, > 90, 54, or 21%, respectively) or with H_2O, NaCl, KCl, KNO_3, $MgCl_2$, or $Mg(NO_3)_2$ (resulting in RHs of > 90, 87, > 90, > 90, 42, or 47%, respectively). One of the reasons for which two different kinds of regression equations were derived between red and black heartwood is assumed to be that the amount of extractives is different (Average of extractive in hot water is 4.4% in red heartwood and 7.4% in black heartwood). Regression equations in sapwood of *C. japonica* (Yamamoto 2013) were also different from those of red and black heartwood in this study. This is because extractives influence the absorption of water molecule, and as Stamm (1929) reported, fiber saturation point changes after removing extractives. However, it is possible that extractives do not influence electrical resistivity, because there were no differences in electrical conductance between sapwood and heartwood (Fredriksson *et al.* 2013). Therefore, the surface MC in this study was calculated from the respective equation derived from the surface electrical resistivity of conditioned red and black heartwood from the same samples in consideration of the other factors affecting electrical resistivity such as density, cell distribution, and kinds of extractives. The surface moisture contents of specimens were derived from the surface electrical resistivity of specimens measured every 5 min during drying, using each regression equation.

RESULTS AND DISCUSSION

As has been shown in previous studies (Sakagami *et al.* 2009a,b; Yamamoto *et al.* 2013), microcracks appeared on the surface of both black and red heartwood when wood specimens were dried at 50 °C and at less than 5% relative humidity.

Moisture Content of Wood Samples

Figure 4 shows the changes in the MC of specimens over time, as determined by weighing the specimens. At the beginning of drying, the MC of the red heartwood specimens was between 35.2 and 70.2% and was lower than that of sapwood. In contrast, the MC of the black heartwood specimens was between 180 and 220%. The total drying time for black heartwood, from GMC to equilibrium moisture content at 50 °C and at 5% relative humidity, was 1.5 to 2 times that of red heartwood, even though the dried samples were small. It has been reported that the drying time for timber that contains black heartwood, using vacuum drying and high-frequency heating, is considerably longer than that for timber containing red heartwood (Kawabe *et al.* 1993). The large difference between the MCs of red and black heartwood is considered to be one of the major problems associated with drying *C. japonica* because it increases the drying cost.

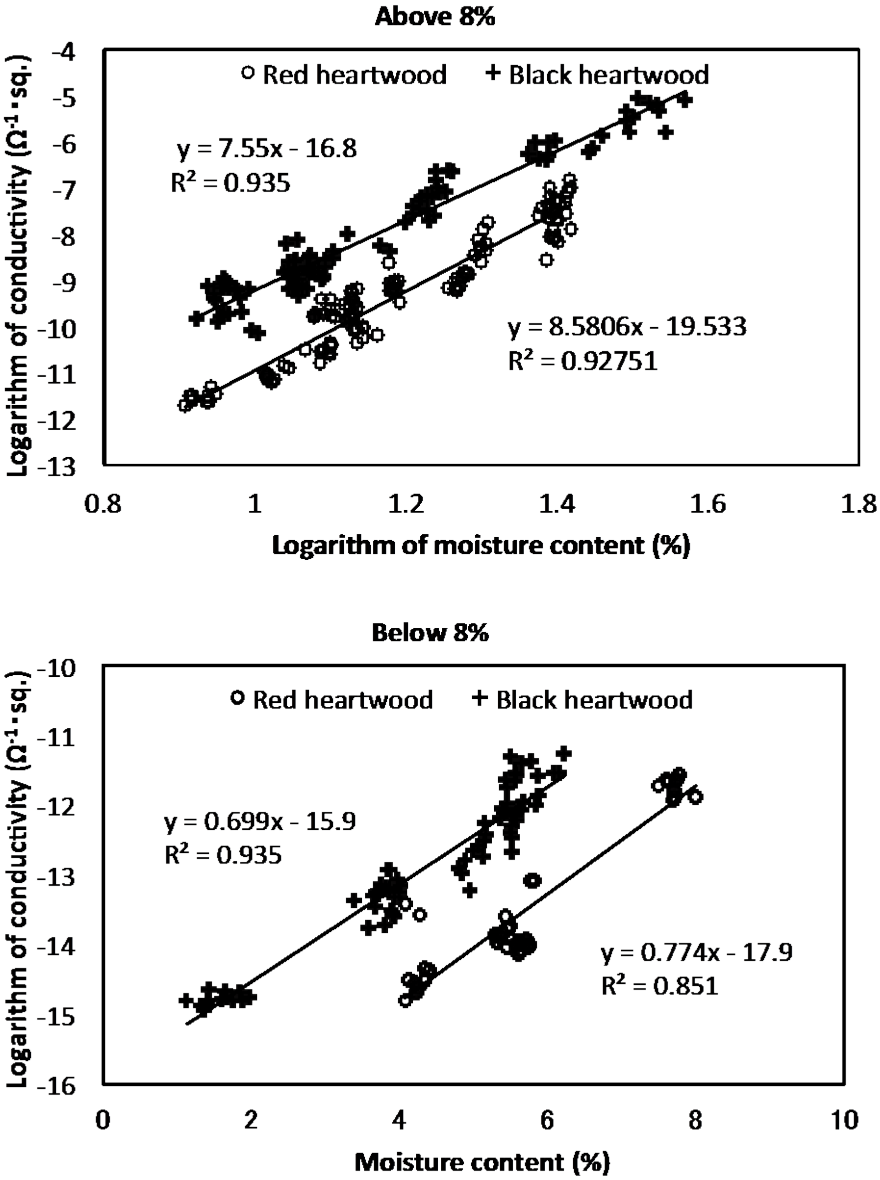

Fig. 3. Relationship between moisture content and conductivity;
(a) Standard curve for the logarithm of surface electrical resistivity *versus* moisture content below 8%. The x-axis represents moisture content, and the y-axis represents the logarithm of surface electrical resistivity. (b) Standard curve for the logarithm of surface electrical resistivity *versus* the logarithm of moisture content above 8%. The x-axis represents the logarithm of moisture content, and the y-axis represents the logarithm of surface electrical resistivity. The sq. stands for square.

Electrical Resistivity of the Surface

Fig. 5 shows the changes in the electrical resistivity of the surface of both heartwoods during drying. In the case of red heartwood, the electrical resistivity of the surface of the wood increased dramatically immediately after drying began. After 3 h, the electrical resistivity was stable and high. However, in black heartwood, the electrical resistivity remained low for the first 2 to 3 h. The electrical resistivity then dramatically increased over the subsequent 2 h. During the final stage of drying, the electrical resistivity remained high.

In general, MC can be calculated from the measurement of electrical resistivity because the conductivity of the direct electric current is associated with MC when the MC is below the fiber saturation point. Therefore, because electrical resistivity changes little when the MC is above the fiber saturation point, the low electrical resistivity in the black heartwood during the first stage of drying indicated that although the wood specimen was drying, free water was still present at the surface. In contrast, high electrical resistivity indicated that the surface of wood specimens was dry. In the intermediate condition, the period during which electrical resistivity increased greatly, the surface moisture was below the fiber saturation point. Development of microcracks occurred in this period, as has been previously reported for sapwood (Yamamoto *et al.* 2013).

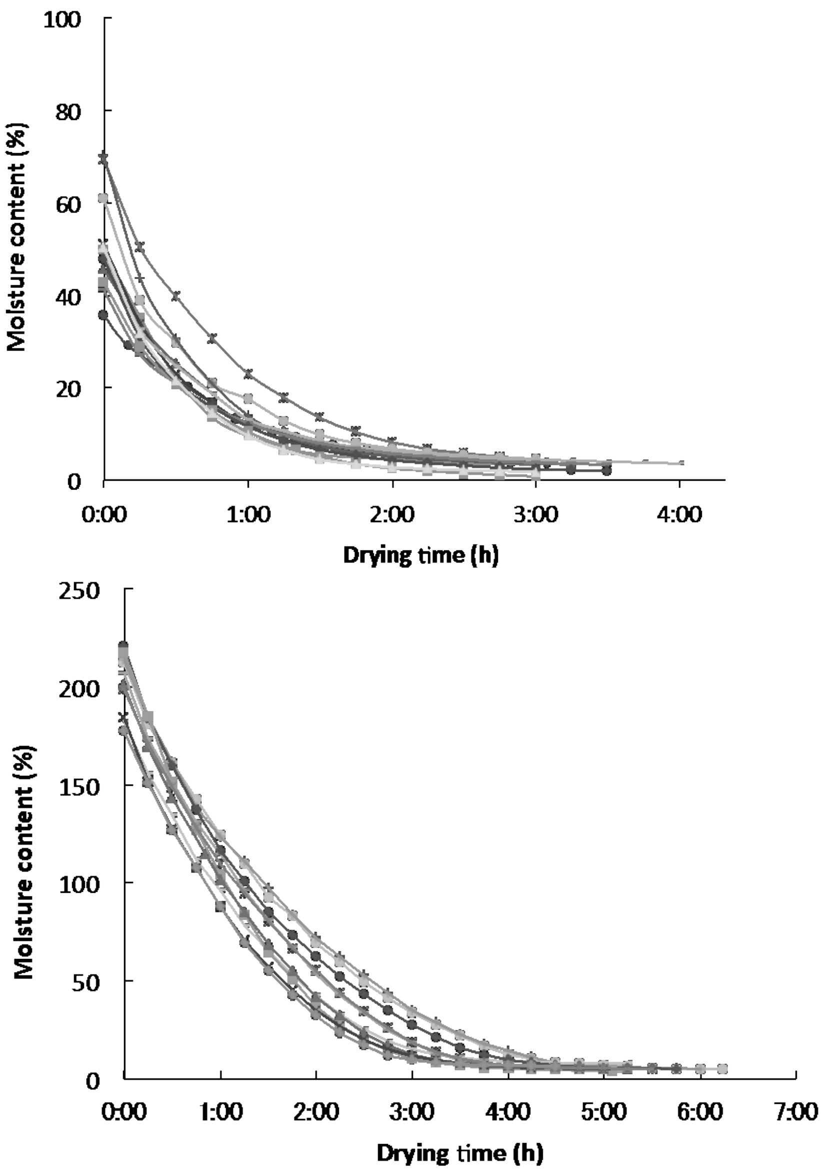

Fig. 4. Relationship between drying time and moisture content as determined from the weights of *Cryptomeria japonica* specimens (upper: 12 samples of red heartwood, lower: 10 samples of black heartwood).

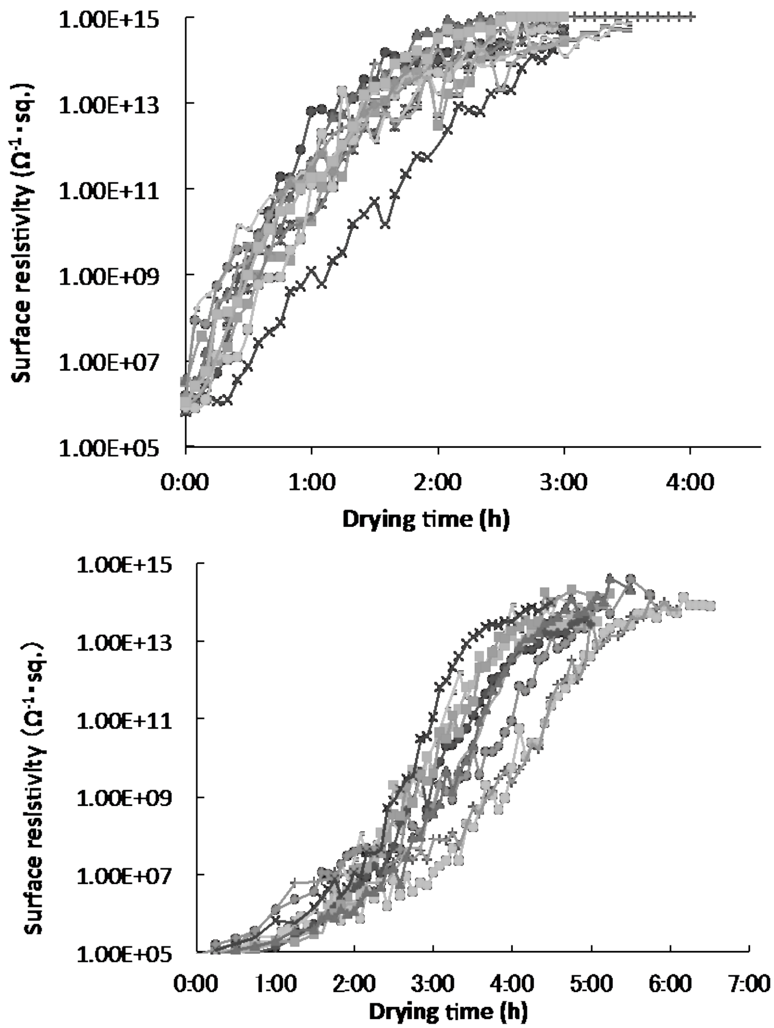

Fig. 5. Changes in electrical resistivity of the surface of *Cryptomeria japonica* heartwood (upper: twelve samples of red heartwood, lower: ten samples of black heartwood); the sq. stands for square.

Microcrack Occurrence

Microcracks occurred on the surface of both red and black heartwood. These microcracks commonly occurred when the electrical resistivity rapidly increased. Figure 6 shows examples of the relationships among microcracks, the MC of the specimens, and the surface MC for each wood type. The surface MC above the fiber saturation point is not shown because at those MCs, there was no relationship between MC and electrical resistivity.

In red heartwood, no microcracks were identified immediately after the initiation of the drying process. It was assumed that the actual MC of the surface was above the fiber saturation point because the electrical resistivity remained low during the initial drying period. After 15 min, the electrical resistivity drastically increased, and micro-cracks appeared in the ray parenchyma or between tracheids and the ray parenchyma in the latewood region, as has been shown in previous studies (Sakagami *et al.* 2009b; Yamamoto *et al.* 2013). When the first microcracks appeared, the MC derived from the oven-dry weight was 33.7%, and the MC of the surface, calculated from the electrical resistivity, was 21.0%. This indicated that surface MC differed from the interior MC.

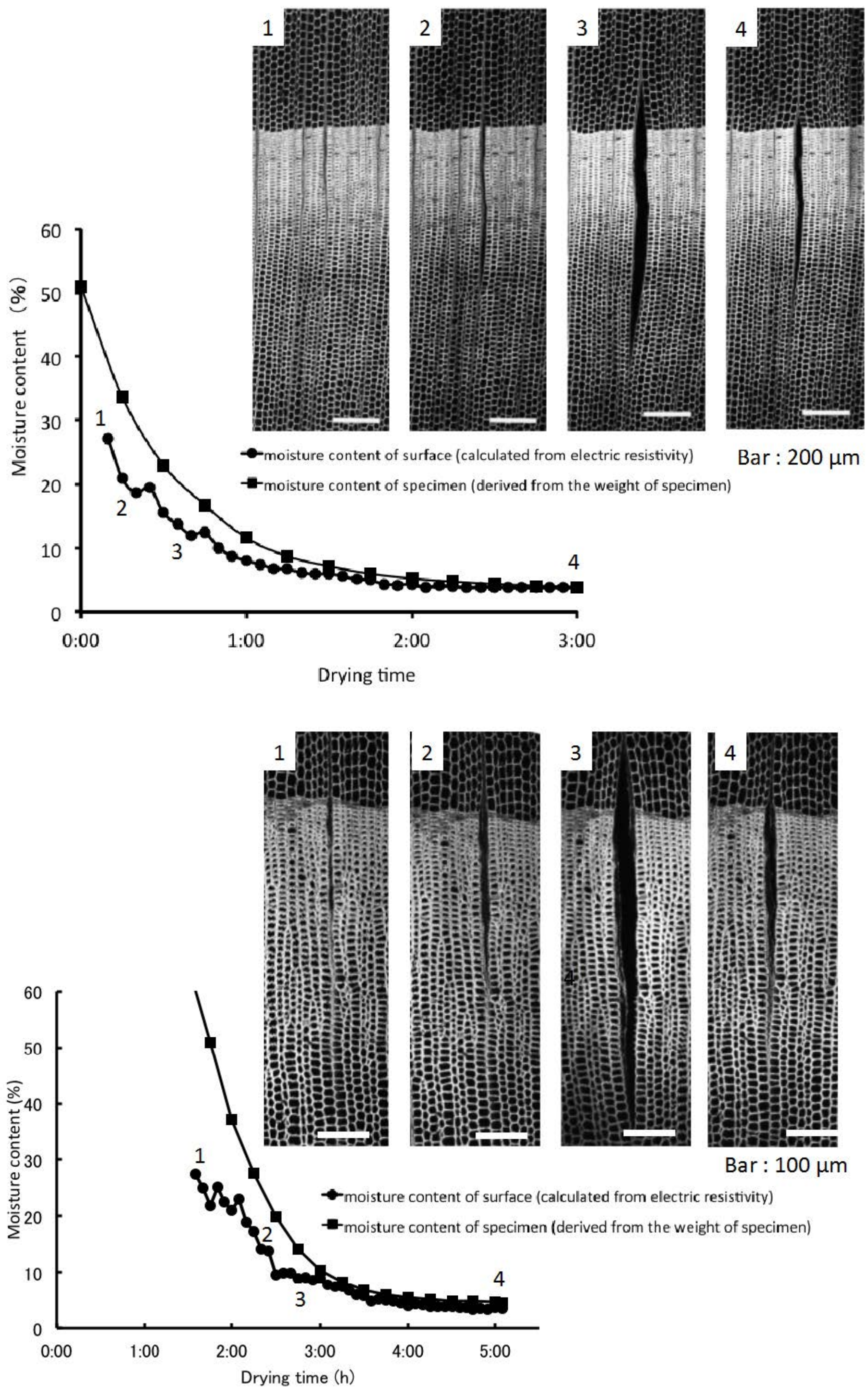

Fig. 6. Relationship between moisture content and microcrack generation in *Cryptomeria japonica* red heartwood (upper) and black heartwood (lower); two types of moisture content, one calculated from electrical resistivity and one determined from the weight of the specimen, are shown.

After the microcracks had propagated along the ray parenchyma toward both the bark and the pith, the propagation slowed and subsequently halted. With further drying, the microcracks gradually closed. However, they were still observable at the end of the drying. The difference between the overall and surface MC measurements was the largest when the microcracks were first generated, but this difference decreased during drying and had almost disappeared by the end of the process.

In black heartwood, no microcracks appeared during the first 2 h of drying. It was assumed that the overall and surface MCs were above the fiber saturation point. After 145 min the surface electrical resistivity increased dramatically and microcracks appeared between the tracheids and ray parenchyma in the latewood region. The surface and overall MC differed during this period, as they did in red heartwood. Subsequently, microcracks spread toward both the bark and the pith. The microcracks then began to close, but persisted until the last stage of drying. As was the case with red heartwood, the differences between the overall and surface MC gradually decreased as the microcracks closed. Microcracks in red and black heartwood commonly occurred in latewood region as in the case of sapwood (Sakagami *et al.* 2009b). This tendency is assumed to influence the growth-ring boundary composed of latewood cells rather than characteristic wood structure of *C. japonica*. Microcracks occurred in the latewood region due to the concentrated stress because shrinkage of latewood is known to be greater than that of earlywood (Nakato 1958; Ma and Rudolph 2006). In the case of the *Acacia* hybrid in which the growth ring boundary is not clear, microcracks randomly distributed on the wood surface (Sakagami *et al.* 2009a).

Although the surface and overall MCs of sapwood were nearly the same in a previous study (Yamamoto *et al.* 2013), the surface MC of black and red heartwood in the present study tended to be lower than the overall MC that was derived from the weight of the specimens. The latewood region of sapwood was assumed to keep moisture longer than the earlywood region, judging from the results of X-ray analysis (Nakanishi *et al.* 1998; Tanaka *et al.* 2009). This Therefore, the moist latewood region where electric current flowed easily was mainly measured prior to earlywood region by the electrical resistivity meter, though moisture content in earlywood region was lower. In contrast to that of sapwood, the gradient of moisture content between earlywood and latewood on the surface of the heartwood did not seem to exist and surface moisture at earlywood and latewood dried together because moisture from surrounding cells was not transported to the latewood due to its low permeability.

Microcrack occurrence is inseparably linked to the MC of wood. Appropriate drying conditions that are suited to the MC of individual wood samples should be applied, even for samples of the same species and wood structure.

CONCLUSIONS

The behavior of microcracks in the black and red heartwoods of *C. japonica* was visualized and compared using a modified CLSM system. These types of heartwood have widely different GMCs, but very similar wood structures. The results were summarized below.

1. There were few morphologic differences between the microcracks in black and red heartwoods.

2. The generation time of microcracks in black heartwood was delayed, whereas the microcracks appeared in red heartwood immediately after drying. The microcracks in red heartwood appeared after 15 min of drying, but it took more than 2 h before microcracks occurred in black heartwood.

From these results, it was concluded that microcrack occurrence is closely linked to the GMC of wood. Therefore, when drying wood materials that have different moisture contents, drying conditions should be tailored to the individual moisture content of the wood samples, even if the samples are from the same species and have the similar wood structure.

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