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ORIGINAL ARTICLE

Microfibril angle and density of hinoki (*Chamaecyparis obtusa*) trees in 15 half-sib families in a progeny test stand in Kyushu, Japan

Yoshio Kijidani · Yoshimitsu Fujii ·
Keita Kimura · Yoshitake Fujisawa ·
Yuichiro Hiraoka · Ryushi Kitahara

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Abstract It was previously believed in Japan that the wood qualities of hinoki (*Chamaecyparis obtusa*) were superior to sugi (*Cryptomeria japonica*). However, few studies of wood properties such as MFA (microfibril angle of S_2 layer in secondary wall of tracheid) have been completed for hinoki. Some reports have found that hinoki plus tree families have similar mechanical properties to sugi. Here we report the characteristics of MFA and density of hinoki half-sib families in a progeny test stand. There were significant differences in MFA and density between families. The wood properties of two families, Nakatsu 3 and Kanzaki 5, are stable in radial pattern and suitable for structural use. Early selection of hinoki families by MFA and density may be difficult. Effects of MFA and density on E_d (dynamic modulus of elasticity) of logs differed between families. The effects of growth rate on MFA and density differed between families and also between juvenile and mature wood. The faster growth rate in Nakatsu 3 appeared to improve wood properties and increase E_d of logs, although in many other families, faster growth rate had negative effects on desirable wood properties for structural use.

Keywords Hinoki plus tree · Microfibril angle · Basic density · Growth rate

Introduction

In 2009, the MAFF (Ministry of Agriculture, Forestry and Fisheries) of Japan developed the “Forest and Forestry Revitalization Plan”. The plan aims to achieve ≥50% wood self-sufficiency within 10 years by developing a reliable domestic wood supply/use system. Hinoki (*Chamaecyparis obtusa*) and sugi (*Cryptomeria japonica*) are important plantation species in Japan. These domestic woods are mainly used for structural use. Therefore, to achieve higher wood self-sufficiency, more reliable and higher mechanical properties of these woods are required. In addition, the color, smell, and durability of heartwood are also important properties especially in hinoki. Hinoki has been considered to have superior quality and be more consistent for timber production than sugi, but some hinoki plus tree (selected as trees with various superior traits, e.g., fast growth and trunk straightness) families have similar stiffness to sugi [1]. Fewer studies have examined the properties of hinoki wood compared with studies on sugi. If the target of wood self-sufficiency rate ≥50% is to be met, more information is required on the properties of hinoki woods.

Recently, rapid prediction of wood stiffness from MFA (microfibril angle of S_2 layer in secondary wall of tracheid) and density was succeeded using SilviScan technology [2]. Using this technology, effects of both MFA and density on mechanical properties were examined in commercially important plantation trees. MFA and density accounted for 96% of the variation of longitudinal MOE (modulus of elasticity) of *Eucalyptus delegatensis* [2]. In eucalypt wood (*Eucalyptus globulus, Eucalyptus nitens* and *Eucalyptus*

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Y. Kijidani (✉) · Y. Fujii · K. Kimura · R. Kitahara
Division of Forest Science, Faculty of Agriculture,
Miyazaki University, Miyazaki 889-2192, Japan
e-mail: kijiyo@cc.miyazaki-u.ac.jp

Y. Fujisawa · Y. Hiraoka
Forest Tree Breeding Center (FTBC),
Forestry and Forest Products Research Institute (FFPRI),
Ibaraki 319-1301, Japan

regnans), MFA and density accounted for 92% of the variation of MOE in bending and MFA had little independent influence on MOR (modulus of rupture) in bending [3]. In Douglas-fir (*Pseudotsuga menziesii*), density was the most contributor to MOE and MOR, and MFA was relatively unimportant [4]. In Sitka spruce (*Picea sitchensis*), both static and dynamic MOE were predicted by MFA and density ($R^2 = 0.725$ and 0.862 respectively) [5]. From these studies, it was assumed that also in hinoki, variation of mechanical properties would be explained by variation of MFA and density. Therefore, the variations of MFA and density within tree and between trees of hinoki should be examined precisely to understand the variation of the mechanical properties.

In conifer, radial patterns of density are different between species. Density in most pines showed low value near the tree center with an increase toward the bark [6]. On the other hand, Norway spruce (*Picea abies*) had high density near the pith and rapid decrease outwards, followed by a small increase [7]. In hinoki, density shows the highest value in juvenile wood, decreasing gradually outwards and becoming constant in older rings [8–10]. Other patterns of radial variation in density were reported for hinoki [11] and red cypress (*Chamaecyparis formosensis*) [12]. Radial variation of density in red cypress was greater than inter-tree variation [12]. Density of hinoki trunks was higher, but more variable, further above ground [10]. In conifers, MFA varies from pith to bark, with the largest angles occurring in the first five to ten growth rings from the pith [13]. In hinoki, MFA showed the largest angle in juvenile wood near the pith and decreased gradually toward the outside, and became a constant at ring number 10–15 [8]. In hinoki, it was reported that variation in compressive strength was mainly affected by the differences of density [9]. Density had little [8] or no [9] effect on MOE. MFA clearly affects MOE than the density of wood [8].

These previous studies of hinoki cited above [8–11] did not include information of genetic background. However, we assume that MFA and density affecting timber quality are genetically controlled. If this is the case, then different families of hinoki can be expected to exhibit different traits and provide different qualities of timber. Providing these traits can be identified, families can be planted to enhance and promote timber quality. There is evidence from studies of hinoki clone (Nangouhi, hinoki cutting cultivar) that the variations in wood properties and mechanical properties in clone tree stands were smaller than those measured in stands of seedling trees [14]. Progeny tests found significant differences in density and E_d (dynamic modulus of elasticity) of logs in different hinoki families [15, 16] and these data imply genetic variation is an important parameter controlling the wood properties in hinoki. It follows that information on MFA and density in different hinoki families would allow the selection of families for desirable traits. However, very few studies have been done on MFA and density of hinoki families.

Fast growth rate is also important characteristic in trees planted for wood production. However, if fast growth reduces the timber quality of hinoki, selecting families for higher growth rates would not be worthwhile. Hinoki plus tree families had larger ring width and slightly smaller density and E_d of logs than the local families [15]. There were also significant differences in ring width, density and mechanical properties between progeny test stands [15]. Studies using stress wave propagation velocity reported that stand age, site class and tree density after thinning affected mechanical properties of hinoki (unknown genetic background) [17]. Densely planted hinoki produces a higher percentage of latewood, with higher density and mechanical properties (unknown genetic background) [11]. It follows that information on the effect of growth rate on MFA and density in identified hinoki families will provide information on potential timber quality.

The purpose of this study was to examine the differences between hinoki families in: (1) the radial variations and absolute value of MFA and density, (2) effects of MFA and density on E_d of logs, and (3) the effects of growth rate on the MFA, density and E_d of logs in hinoki family grown as part of a progeny test stand. In this study, according to the data obtained at 1.2 m above ground, the difference between hinoki families were discussed. Therefore, the difference between hinoki families at the other height in the stems remains unclear.

Materials and methods

Materials

Hinoki half-sib families in the progeny test stand were planted in Oita prefecture, Japan in 1974 by Forest Tree Breeding Center (FTBC), Forestry and Forest Products Research Institute (FFPRI). Hinoki trees (31 families × 2 replicates × 49 trees) were planted at 1.8 m spacing and the stands were not managed by silvicultural practice. Sample trees (31 families × 2 replicates × 3 trees) were harvested at 29 years old, and then the E_d of 2 m log at 1–3 m above ground and DBH (diameter at breast height) were measured [1]. This study found E_d of logs was significantly different and DBH was not significantly different between half-sib families [1]. In the present study, 15 half-sib families (12 plus tree families and 3 local families) with different E_d of logs to each other and five trees with different DBH and E_d of logs to each other per family were selected from the harvested sample trees in previous study [1]. This gave a total sample size of 75 hinoki trees

(15 half-sib families × 5 trees) (Table 1). The local families in this progeny test stand were the families, which had been selected and bred as families with superior traits before the project of plus tree selection started and the plus tree seedlings were able to be utilized. In this study, the local families were examined not as controls in progeny test stands but as important genetic resources.

Measurements of ring width, density and MFA

The ring width, density, and MFA of each tree were measured from a 20 cm length of trunk at 1.2 m above ground. An edge grain board with the pith in the center was cut into three parts, in longitudinal direction. In the present study, we estimated the wood of ring number $\leq$10 and the wood of ring number $\geq$11 as juvenile wood and mature wood, respectively. In generally, variations of MFA and density in juvenile wood differ from those in mature wood. One of the purposes of this study was on the effect of growth rate on MFA and density. We guessed that effect of growth rate on MFA and density in juvenile wood might differ from that of mature wood. Therefore, we tried to examine the effect of growth rate on MFA and density in juvenile wood and mature wood, separately. Ring widths on the both sides from pith to ring number 25 were measured and averaged. DBH (10) and DBH (25) in Table 1 were calculated from the sum of ring widths up to ring number 10 or 25.

Density was measured from 3–6 sub-samples (2 cm width in radial direction) of edge grain wood cut from pith to bark on each side. Heartwood extractives were removed by immersing samples in methanol (72 h, room temperature) and hot water (48 h, 90°C). Density was calculated from green volume and kiln dry weight. The variation of density was measured from pith to bark on both sides. Although we measured basic density of samples, in this study, we described basic density as "density".

MFA of tangential wall was measured from 24 µm thick tangential sections cut from latewood of ring numbers 5, 10, 15, 20 and 25 on one side of edge grain specimens. MFA was measured by the iodine-staining method [18]. I_2 crystallizes in gaps between microfibrils and sections were observed with a light microscope. On light microscopy, MFA was measured using image analysis software (Image J [19]). MFA of each ring was obtained by averaging the MFA of 30 latewood tracheids.

Statistical analysis

By one-way analysis of variance and multiple comparisons (statistical analysis software, SPSS ver. 16 with Regression and Advanced Models), the significant difference of measurements between families was examined. The number of families and replications used for this study was small. Therefore, data from two replicates for each family were combined, and analyzed by one-way ANOVA and then by Tukey HSD test and Bonferroni test. The results by different multiple comparisons tests were almost the same.

Results and discussion

Genetic variation of MFA and density

The MFA and density differed between families (Table 2), although environmental effects could not be evaluated because of small sample size. We assumed to be able to identify the characteristics of families in MFA and density by using these samples of half-sib families.

Table 1 Sample trees from 15 half-sib families

Family number	Family name	Prefecture	*n*	DBH (25) (cm)	DBH (10) (cm)	E_d (GPa)
1	Onga 1	Fukuoka	5	17.4 (13.9)	10.6 (6.5)	10.5 (12.6)
2	Yamada 2	Fukuoka	5	18.3 (11.6)	10.0 (18.2)	8.7 (15.6)
3	Ukiha 13	Fukuoka	5	17.4 (7.2)	9.7 (12.0)	9.8 (14.9)
4	Kanzaki 5	Saga	5	18.7 (7.6)	10.4 (12.9)	9.9 (5.6)
5	Nankourai 2	Nagasaki	5	17.2 (7.2)	10.7 (6.9)	9.2 (15.7)
6	Takedasho 2	Oita	5	16.0 (18.3)	9.1 (6.8)	10.1 (10.4)
7	Kusu 6	Oita	5	16.3 (11.3)	9.6 (15.0)	10.8 (14.0)
8	Saeki 5	Oita	5	18.1 (15.1)	10.5 (16.4)	9.0 (8.9)
9	Kikuchi 1	Kumamoto	5	18.2 (18.0)	11.0 (9.4)	9.0 (8.3)
10	Aira 2	Kagoshima	5	16.3 (19.0)	9.4 (2.8)	8.2 (5.1)
11	Isa 1	Kagoshima	5	16.0 (13.2)	9.7 (11.5)	9.5 (7.4)
12	Kitamorokata 2	Miyazaki	5	17.2 (15.5)	10.1 (15.4)	9.3 (18.6)
13	Oita	Oita	5	16.2 (17.9)	8.6 (10.9)	9.9 (9.4)
14	Nakatsu 1	Oita	5	16.2 (10.2)	9.1 (9.0)	9.8 (7.0)
15	Nakatsu 3	Oita	5	18.6 (8.2)	10.6 (9.3)	10.2 (7.1)

No. 1–12 are plus tree families No. 13–15 are local families in Oita prefecture. The values of DBH and Ed represent the averages of tested trees and the values of parentheses represent the coefficient of variation (%). Prefecture is the prefecture from where the trees are selected

n number of samples, *DBH (25) and DBH (10)* diameter at breast height in 25 years old and 10 years old, respectively

Nakatsu 3 and Oita are the families with smaller MFA and Kitamorokata 2 and Aira 2 are the families with larger MFA (Fig. 1). By multiple comparisons, it was recognized that Nakatsu 3 and Oita had statistically smaller overall MFA than Kitamorokata 2 ($p < 0.01$). Overall MFA of each family ranged from 11.4 to 19.1 degrees. The variation of MFA in juvenile wood (average rings ≤ 10) was larger than the MFA of mature wood (average rings ≥ 11) and family characteristic MFA was clearer in juvenile wood. In sugi cultivars, the effect of MFA on MOE was larger where MFA $\leq 15°$ [20]. If this relationship also applies to hinoki, although mature wood MFA is less variable than juvenile wood MFA, the variation of mature wood MFA may be an important trait affecting overall mechanical properties of the timber.

We found that density was higher in Kusu 6, Takedasho 2 and Onga 1 than in Yamada 2, Aira 2 and Nankourai 2 (Fig. 2). By multiple comparisons, it was recognized that Kusu 6 had statistically higher overall density than Yamada 2 ($p < 0.05$). Overall density of each family ranged from 365 to 413 kg/m^3. Juvenile wood density was larger than mature wood density in all families. The results from the present study are similar to previous reports [8–10]. The variation of density in juvenile wood (average rings ≤ 10) was less than the density of mature wood (average rings ≥ 11) and family characteristic density was clearer in mature wood.

A comparison of juvenile wood and mature wood (Figs. 1, 2) shows some difference in radial variation patterns of MFA and density between families. In samples, MFA was larger in rings near the pith and became smaller in outer rings. However, the rates of decrease of MFA were different between families (Fig. 3). In Nakatsu 3, MFA decreased rapidly from ring number 5 to ring number 10 and then remained constant in all trees except one. In Aira 2, MFA decreased gradually from ring number 5 to ring number 25. In Isa 1, there were trees with the both rapid and gradual decrease patterns of MFA. These patterns of radial variation in MFA allow the 15 half-sib families to be classified into three groups: rapid decrease; gradual decrease; and mixed decrease. Nakatsu 3, Oita and Kanzaki 5, families with smaller overall MFA (Fig. 1), formed a rapidly decrease group. Nankourai 2, Kikuchi 1, Ukiha 13, Saeki 5, Takedasho 2, Aira 2 and Kitamorokata 2, families with larger overall MFA (Fig. 1) formed a gradually decrease group. Onga 1, Nakatsu 1, Kusu 6, Yamada 2 and Isa 1, families with medium overall MFA (Fig. 1), formed a mixed decrease group. As smaller and stable MFAs are a desirable feature in timber production, the families in the rapid decrease group might be suitable for structural timber.

In all samples, density was larger in rings near the pith and became smaller in the outer rings, but the absolute decrease in density differed between families (Fig. 4). In Takedasho 2, density slightly decreased from ring number 5 to ring number 10–15 and thereafter density remained at 350–450 kg/m^3. In Ukiha 13, there was a moderate decrease in density from ring number 5 to ring number 15; thereafter density stayed at 350–400 kg/m^3. In Yamada 2, there was a great decrease in density from ring number 5 to ring number 15–25; thereafter, density remained at 300–400 kg/m^3. The patterns of radial variation of density,

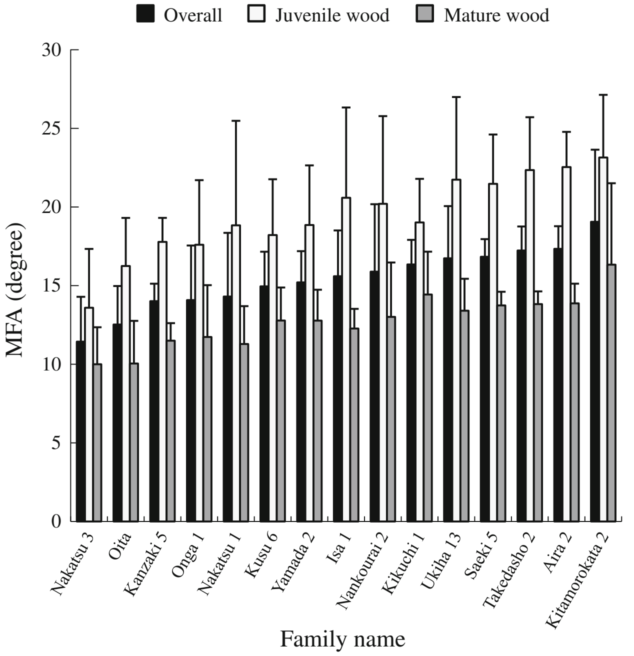


Fig. 1 MFA of hinoki trees from 15 half-sib families. The order was according to MFA (overall), MFA of each family was average of 5 trees, *error bar* standard deviation

Table 2 Analysis of variance

Source of variation	MFA					Density				
	SS	*df*	MS	*F* value	*p* value	SS	*df*	MS	*F* value	*p* value
Between families	272.858	14	19.49	2.444	0.009	13370.333	14	955.024	2.368	0.011
Within families	478.49	60	7.975			24198.198	60	403.303		
Total	751.347	74				37568.531	74			

MFA and density were averaged value of all measured rings in each trees

SS sum of squared deviation, *df* degree of freedom, *MS* mean square allow the 15 half-sib families to be classified into three groups: slight decrease; moderate decrease; and great decrease. Families with larger overall density (Kusu 6, Takedasho 2, Onga 1, Nakatsu 3 and Kanzaki 5 in Fig. 2) formed a slight decrease group. Families with medium overall density (Nakatsu 1, Kikuchi 1, Ukiha 13, Saeki 5, Kitamorokata 2, Isa 1 and Oita in Fig. 2) formed a moderate decrease group. Families with smaller overall density (Nankourai 2, Aira 2 and Yamada 2 in Fig. 2) formed a great decrease group. As a larger and more stable density is a desirable trait, families in the slightly decrease group might be suitable for structural timber.

As Nakatsu 3 and Kanzaki 5 exhibit desirable traits in MFA (rapid decrease) and density (slight decrease), these two families are potential candidates for structural timber production with superior and stable wood properties. Recently, demands for laminated wood become larger because of more reliable quality and higher performance in comparison with solid wood year by year. The performance of laminated wood for structural use mainly depends on the mechanical properties of each lamina in laminated wood. The traits in MFA (rapid decrease) and density (slight decrease) found in this study may contribute to produce larger number of high quality lamina from each hinoki log.

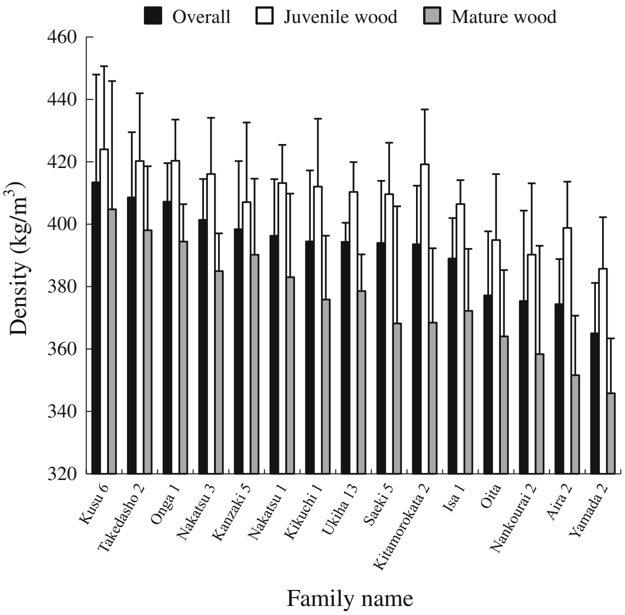


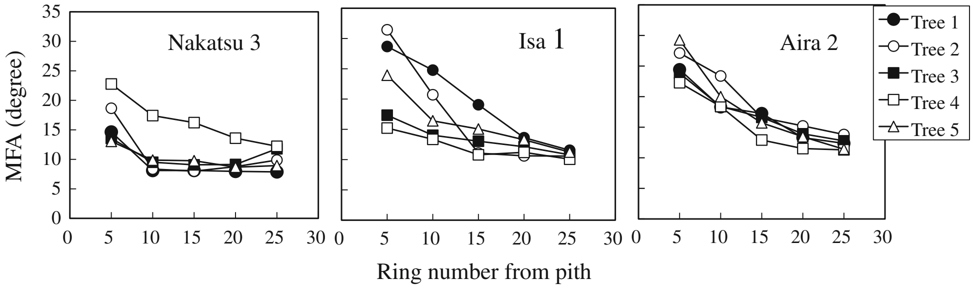
Fig. 2 Density of hinoki trees from 15 half-sib families. The order was according to density (overall), Density of each family was average of 5 trees, *error bar* standard deviation

If MFA and density in younger rings have strong correlations between MFA and density in older rings, families with desirable traits will be more efficiently selected in early time. To access the possibility of early time selection of hinoki families, the relationships between values of MFA and density in juvenile and mature wood were examined. As shown in Fig. 5, MFA at ring number 5 was not correlated with MFA at ring number 25, and density of the innermost sample was not correlated with density in the outmost sample ($p > 0.05$). The reason of poor correlations assumed to be the different radial variation pattern between families shown in Figs. 3 and 4. This data implies that prediction accuracy may be insufficient to allow early selection of families for desirable MFA and density traits, although this assumption was based on only 15 families.

Effects of MFA and density on Ed of logs

In the present study, E_d of logs was negatively correlated with MFA ($p < 0.01$), and positively correlated with density ($p < 0.01$) (Fig. 6). We found Aira 2 family to have the smallest E_d of logs and Nakatsu 3 to have the larger E_d of logs (Table 1). We assume the low value for E_d of logs in Aira 2 is related to the larger MFA and smaller density, and that the larger E_d of logs of Nakatsu 3 was related to a smaller MFA and medium density (Fig. 6). When all families were combined together, the effects of MFA and density on E_d of logs were similar ($R = -0.54$, 0.54 respectively). In a previous study of hinoki of unknown genetic background [8], the effect of MFA on MOE was greater than that of density. As described before, in Douglas-fir (*Pseudotsuga menziesii*), density was the most contributor to MOE and MOR, and MFA was relatively unimportant [4]. In small clear specimens of sugi cultivars, the effect of MFA on MOE in longitudinal compression was larger than that of density [20]. In sugi timber, the

Fig. 3 Radial variations of MFA of hinoki three families. Nakatsu 3, Isa 1 and Aira 2 are the family with smaller, medium and larger MFA in 15 families, respectively (Fig. 1)



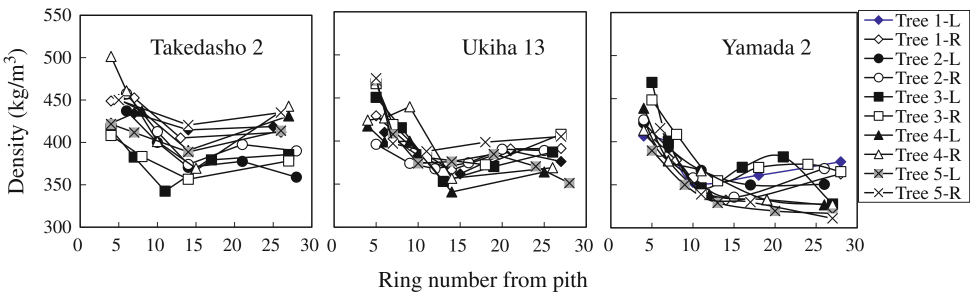


Fig. 4 Radial variations of density of hinoki three families. Takedasho 2, Ukiha 13 and Yamada 2 are the family with larger, medium and smaller density in 15 families, respectively (Fig. 2). Tree 1-L and Tree 1-R mean one and the other side of radial direction in Tree 1

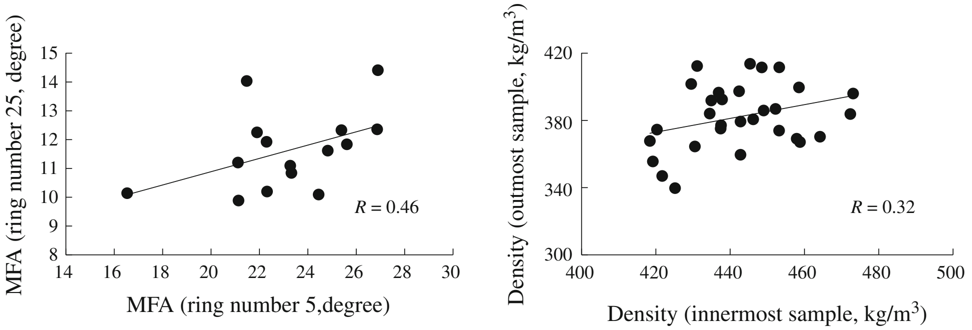


Fig. 5 Early time prediction of MFA and density of outer wood of families. Innermost sample and outmost sample are samples including several rings near 5 and 25, respectively. Each family has two density data, because density was measured on both side from pith

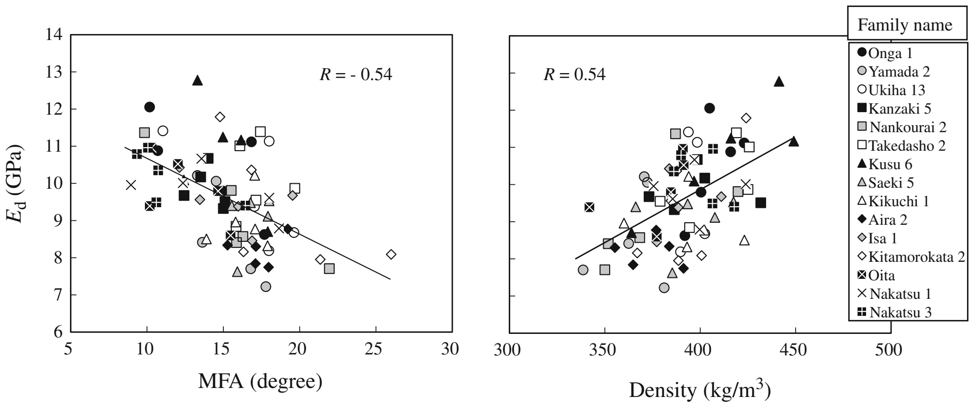


Fig. 6 Effects of MFA and density on E_d of logs of hinoki trees from 15 families MFA and density are average of all measured rings

effect of MFA on MOE in bending was larger than density [21]. MFA accounted for 80% of variation of MOE in compression of obi-sugi small clear specimens [20]. This implies the effect of density on mechanical properties is larger in hinoki than in sugi.

To access the effect of genetic variation, correlation coefficients between MFA and E_d of logs, and those between density and E_d of logs were shown in Table 3. It was found that the effects of MFA and density on E_d of logs were different between families. In Yamada 2, Ukiha 13, Nankourai 2, Nakatsu 1 and Nakatsu 3, correlation coefficients of MFA were larger than those of density. In Takedasho 2 and Kusu 6, correlation coefficients of density were larger than those of MFA. In the other families, correlation coefficients of MFA and density were almost same or very small value. From these results, it was demonstrated that genetic variations also affected to the relationships between MFA, density and stiffness.

Effects of growth rate on MFA, density and E_d of logs

In Table 4, DBH (10) in Table 1 was used as the growth rate of juvenile wood, the growth rate of mature wood was evaluated by the difference between DBH (25) and DBH (10), and DBH (25) in Table 1 was used as the growth rate of overall logs. The effects of growth rate on MFA and density were different between families and also different between juvenile and mature wood in each family, as shown in Table 4.

The effect of growth rate was positive on juvenile wood MFA in Kanzaki 5 and Isa 1; positive on mature wood MFA in Kusu 6; negative on juvenile wood density in Takedasho 2; and negative on mature wood density in Nankourai 2. As smaller MFA and larger density increase E_d of logs (Fig. 6), a faster growth rate in these five families would reduce wood properties for structural use. In contrast, the effect of growth rate on other families was:

Table 3 Effect of MFA and density on E_d of logs in each family

Family number	Family name	Prefecture	n	Correlation coefficient	
				MFA	Density
1	Onga 1	Fukuoka	5	−0.71	0.66
2	Yamada 2	Fukuoka	5	−0.81	0.25
3	Ukiha 13	Fukuoka	5	−0.67	0.17
4	Kanzaki 5	Saga	5	−0.32	0.01
5	Nankourai 2	Nagasaki	5	−0.91*	0.68
6	Takedasho 2	Oita	5	0.07	0.67
7	Kusu 6	Oita	5	−0.54	0.88*
8	Saeki 5	Oita	5	0.41	0.23
9	Kikuchi 1	Kumamoto	5	0.19	−0.21
10	Aira 2	Kagoshima	5	0.24	−0.14
11	Isa 1	Kagoshima	5	−0.49	0.30
12	Kitamorokata 2	Miyazaki	5	−0.68	0.68
13	Oita	Oita	5	−0.61	0.53
14	Nakatsu 1	Oita	5	−0.63	0.03
15	Nakatsu 3	Oita	5	−0.70	−0.57
	All families		75	−0.54**	0.54**

* Significant at 5% level,
** Significant at 1% level

Table 4 Effect of growth rate on MFA, density and E_d of logs in each family

Family number	Family name	Prefecture	n	Correlation coefficient				
				MFA		Density		E_d
				Juvenile wood	Mature wood	Juvenile wood	Mature wood	
1	Onga 1	Fukuoka	5	0.37	0.11	0.68	0.69	−0.13
2	Yamada 2	Fukuoka	5	0.42	0.38	0.00	0.17	−0.60
3	Ukiha 13	Fukuoka	5	0.50	0.50	0.60	0.93*	−0.19
4	Kanzaki 5	Saga	5	0.88*	0.14	0.10	0.50	−0.45
5	Nankourai 2	Nagasaki	5	−0.42	0.74	0.05	−0.92*	−0.63
6	Takedasho 2	Oita	5	−0.20	0.35	−0.91*	0.59	−0.85
7	Kusu 6	Oita	5	−0.65	0.97**	0.50	0.18	0.15
8	Saeki 5	Oita	5	0.05	0.07	−0.34	0.51	−0.66
9	Kikuchi 1	Kumamoto	5	0.09	0.42	0.20	−0.33	−0.06
10	Aira 2	Kagoshima	5	0.06	0.41	0.58	−0.40	0.17
11	Isa 1	Kagoshima	5	0.97**	0.60	0.01	0.56	−0.58
12	Kitamorokata 2	Miyazaki	5	0.19	0.08	0.13	−0.51	−0.78
13	Oita	Oita	5	0.15	0.67	0.53	0.34	−0.27
14	Nakatsu 1	Oita	5	0.41	0.68	0.18	0.18	−0.82
15	Nakatsu 3	Oita	5	−0.89*	−0.62	0.15	0.69	0.83
	All families		75	0.01	0.10	0.03	−0.11	−0.28*

DBH (10) in Table 1 was used as growth rate of juvenile wood

DBH (25) in Table 1 was used as growth rate for E_d of logs

DBH (25)–DBH (10) was used as growth rate of mature wood

* Significant at 5% level

** Significant at 1% level

Ukiha 13, positive on mature wood density; Nakatsu 3, negative on juvenile wood MFA. Therefore, in these two families, faster growth rate improved wood properties for structural use. Growth rate rarely affected MFA or density in Yamada 2, Saeki 5 and Kitamorokata 2. As shown in Table 4, there was no significant effect of growth rate on E_d

of logs in each family. In most families, the correlation coefficient between growth rate and E_d of logs were negative. Therefore, when all families were combined together, increased growth rate significantly reduced E_d of logs ($p < 0.05$). In contrast, in Nakatsu 3, the correlation coefficient between growth rate and E_d of logs was positive and larger than in other families ($R = 0.83$). E_d of logs and DBH (25) were also larger, and the pattern of MFA and density differed in Nakatsu 3 from other families (Table 1 and Fig. 3). Faster growth rate also produced moderate improvements in mature wood MFA and mature wood density, although the correlations were not significant ($R = -0.62$ and 0.69, respectively). We infer from these results, Nakatsu 3 would be suitable hinoki family for timber production. Onga 1 might also be suitable, as this family has a larger E_d of logs (Table 1), the effect of growth rate on MFA was small, and there was a positive correlation coefficient between growth rate and density (Table 4). In slash and loblolly pine, fertilization treatments have short-term negative effects (2–3 years) on density, and in the plantation of these species in the southeastern United States, mid-rotation fertilization is a common silvicultural practice and contributes to growth benefit [22]. In slash pine grown in Japan, fast growth induced no negative effects on MFA, density and mechanical properties in bending [23]. Therefore, for lumber production of hinoki plantation for structural use, characteristic of Nakatsu 3 shown in Table 4 assumed to be very important. This study was limited to only 15 families, and there may be the other hinoki families with the same characteristic as Nakatsu 3. The hinoki plantation of the families with the same characteristic as Nakatsu 3 may enable to increase in volume production and shorten the rotation period without decrease the wood quality for structural use.

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