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ORIGINAL ARTICLE

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Radial variations of wood properties of an endangered species, *Pinus armandii* var. *amamiana*

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Abstract A dead tree of *Pinus armandii* Franch. var. *amamiana* (Koidz.) Hatusima (abbreviated to PAAm) was obtained from a natural habitat on Tanega-shima Island and various properties of its wood were investigated. Grain angle was measured and soft X-ray analysis was undertaken to obtain the density in each annual ring. Unit shrinkage and dynamic properties were measured by shrinkage, bending, and compression tests. Variations of wood properties in the radial direction, relationships of wood properties to density, and annual ring width were examined. Roughly speaking, variations in the radial direction of the grain angle, twist angle by drying, Young's modulus and strength in static bending, absorbed energy in impact bending, compressive Young's modulus, compressive strength, and compressive proportional limit corresponded to the variation of annual ring width. As a result, it was determined that if PAAm is afforested artificially for the purposes of lumber production and conservation, the annual rings of logs should not be too widely spaced. Wood properties of PAAm were similar to those of Japanese black pine (*Pinus thunbergii* Parl.), which is another representative pine on Tanega-shima Island.

Key words *Pinus armandii* var. *amamiana* · Wood properties · Tanega-shima Island · Endangered species

Introduction

Pinus armandii Franch. var. *amamiana* (Koidz.) Hatusima (abbreviated to PAAm hereafter) is an evergreen five-needle pine species endemic to Tanega-shima and Yaku-shima Islands, southwestern Japan.[1,2] The species grows to 300 cm in diameter at breast height and 30 m in height. This pine species is closely related to *P. armandii* var. *armandii* and *P. armandii* var. *mastersiana*, which are distributed in the western part of continental China and in the highlands of Taiwan, respectively.[2]

The wood of PAAm has been traditionally used for making fishing canoes and also in house construction.[3,4] However, in recent years, PAAm wood has not been used, and the number of surviving PAAm trees has rapidly declined. Dead PAAm trees are frequently observed in natural habitats.[5,6] Several factors are responsible for the decline of this pine species over a few decades, including human activities,[3,4] inbreeding depression,[7,8] reduced natural regeneration,[9–13] and pine wilt disease.[5,14,15]

Currently, the estimated number of surviving PAAm trees in natural habitats is only 300 on Tanega-shima Island and 1500–2000 on Yaku-shima Island.[16] Hence, PAAm has been classified as endangered in the Japanese Red List, due to the rapid decrease in and fragmentation of its population, which denote a high possibility of extinction in the near future.[17]

For conservation and regeneration of PAAm, various approaches have been tried. For example, PAAm trees have been grafted for establishment of demonstration forests and seed stands on both islands.[18] Plant regeneration from mature embryos using in vitro propagation techniques was also achieved.[19,20]

Conservation of an endangered tree species can be aided by promoting utilization of its wood. The Monterey pine (*Pinus radiata* D. Don), which is an important export timber in New Zealand, is one of the best examples. This pine is not native to New Zealand but was a rare species that was distributed naturally in a limited area along the Pacific coast in the San Francisco area in North America.[21] Today, the

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Monterey pine is no longer endangered because it is planted for wood utilization. As with the Monterey pine, the threat of extinction of PAAm will be removed in the future if the species is planted and used for many applications.[16,22,23]

Although PAAm must have basic wood properties to be used as commercial timber, little is known about it. Fortunately, we could obtain a thick log of PAAm to investigate its wood properties. In this study, we measured the grain angle and soft X-ray analysis was undertaken to obtain the density in each annual ring. Unit shrinkage and dynamic properties were measured by shrinkage, bending, and compression tests. Variations of wood properties in the radial direction, relationships of wood properties to density, and annual ring width were examined. We believe that these results will be useful in the future when PAAm is afforested artificially for the purposes of lumber production and conservation.

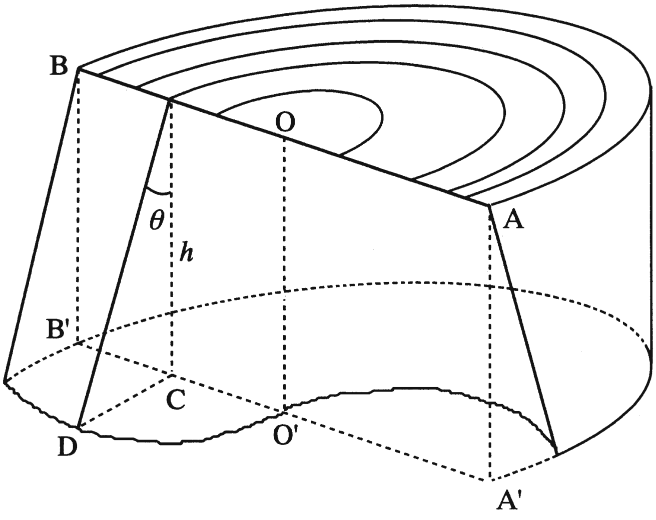

Fig. 1. Illustration of the method of examination by splitting

Materials and methods

Specimens

Specimens were obtained from a dead PAAm tree from the Sendan-no-mine National Forest (30°36′13″N, 131°0′19″E, 190 m above sea level) on Tanega-shima Island in southwestern Japan. The tree was 70 years old and its diameter at breast height was 480 mm.

The mortality factor of this tree is unknown, and it was cut in February 2006 just after we found total foliage discoloration. This tree stem was cut for logs of 40–50 cm in length, and these logs were transported to the Forestry and Forest Products Research Institute (Tsukuba city) in May 2006.

Several boards with thicknesses of 60–120 mm (T) including the maximum diameter were cut from the log. The boards were used for the following tests.

Grain angle

A specimen having dimensions of 50 mm (T) by 100 mm (L) was made from a board. Its dimension in the radial (R)-direction was the maximum diameter. A hatchet was used to split the specimen along its diameter in the L-direction. The grain angle of the green wood was calculated by $\tan^{-1} CD/h$, as shown in Fig. 1.[24]

Soft X-ray measurements

To obtain annual ring width, soft X-ray analysis was conducted on a 20 mm (T) by 2 mm (L) sample. Its dimension in the R-direction was the maximum diameter. It was conditioned at 20°C and 65% relative humidity (RH). A soft X-ray generated at 20 kV and 14 mA was applied to the cross section and penetrated through the sample for 4 min.

Twist by drying

Specimens having dimensions of 10 mm (R) by 120 mm (T) by 255 mm (L) were made. Twist angle (θ) after oven drying at 105°C from green wood was measured with a protractor.

Shrinkage test

Specimens having dimensions of 30 mm (R) by 5 mm (T) by 60 mm (L) (LR-plane specimens) and 30 mm (R) by 30 mm (T) by 5 mm (L) (RT-plane specimens) were made. They were air-dried at 20°C and 65% RH and then oven-dried at 105°C. Unit shrinkage (from air dry to oven dry) in the L-direction (δ_L) was measured with the LR-plane specimens, and unit shrinkages in the R-direction (δ_R) and that in T-direction (δ_T) were measured with the RT-plane specimens according to Japanese Industrial Standard (JIS) Z 2101-1994.

Static bending test

Specimens having dimensions of 7 mm (R) by 7 mm (T) by 120 mm (L) were made and conditioned at 20°C and 65% RH before and during the tests. A static bending test was conducted using center-point loading over a 98-mm span with the load applied in the tangential direction. The crosshead speed was 5 mm min^{-1}. From the load–deflection curve, the static Young's modulus (E_{sb}) and the bending strength (σ_{sb}) were obtained.

Impact bending test

Specimens having dimensions of 7 mm (R) by 7 mm (T) by 120 mm (L) were made and conditioned at 20°C and 65%

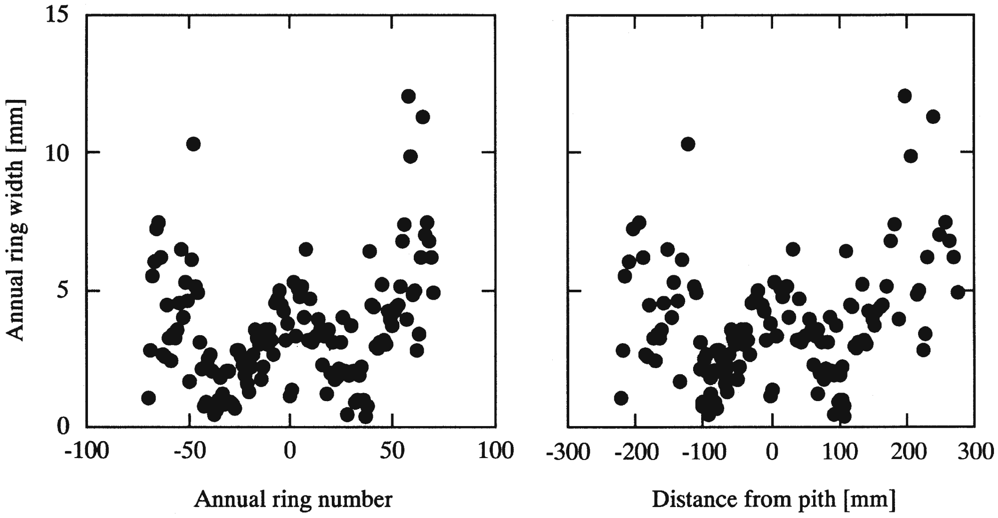

Fig. 2. Variation of annual ring width as a function of annual ring number (*left*) and as a function of distance from the pith (*right*)

RH before and during the tests. A Charpy-type impact bending machine with a capacity of 30 kgw cm was used to obtain the absorbed energy in impact bending (W_{ib}). The span was 84 mm.

Compression test

Specimens having dimensions of 20 mm (R) by 20 mm (T) by 40 mm (L) (L-direction specimen), 20 mm (L) by 20 mm (T) by 40 mm (R) (R-direction specimen), and 20 mm (L) by 20 mm (R) by 40 mm (T) (T-direction specimen) were made and conditioned at 20°C and 65% RH before and during the tests. Biaxial strain gauges (FCA-2-11, Kyowa Electronic Instruments, gauge length 2 mm) were bonded to each side of the specimen. The load was applied along the long axis of the specimen at the loading velocity of 1 mm min^{-1} to obtain the stress–strain relationships. From the stress–strain relationships, Young's modulus (E_{cL}, E_{cR}, and E_{cT}), compression strength (σ_{cL}), proportional limit (P_{cR} and P_{cT}), and Poisson's ratio (ν_{LR}, ν_{LT}, ν_{RL}, ν_{RT}, ν_{TL}, and ν_{TR}) were obtained. The values of E_{cL}, σ_{cL}, ν_{LR}, and ν_{LT} were obtained using the L-direction specimen. The values of E_{cR}, P_{cR}, ν_{RL}, and ν_{RT} were obtained using the R-direction specimen. The values of E_{cT}, P_{cT}, ν_{TL}, and ν_{TR} were obtained using the T-direction specimen.

Results and discussion

Figure 2 shows the variation of annual ring width in the R-direction. The negative values of annual ring number and distance from the pith in this figure and the figures mentioned below denote a shorter radius.

The growth rate decreased for the first 30 years or so and increased after that. This result suggests that there was competition from other trees in its growth process. This variation pattern is called "W-type" in this article.

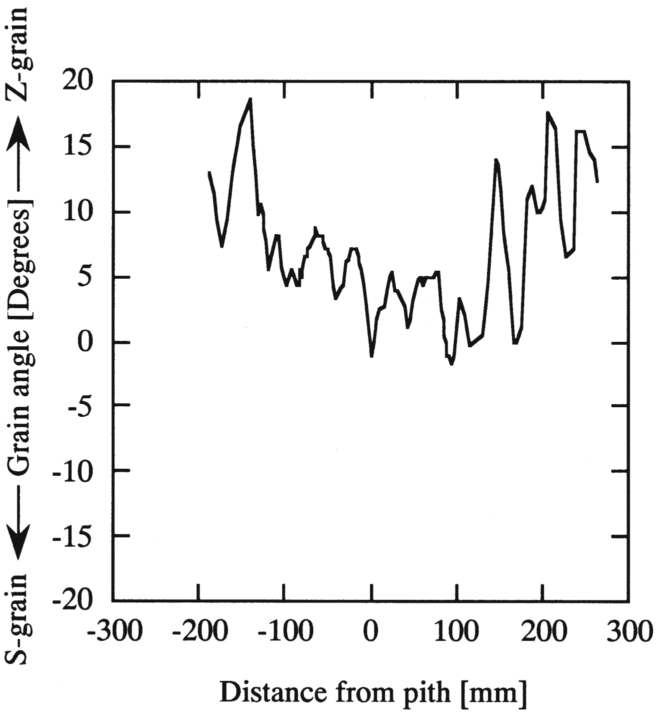

Fig. 3. Radial variation of grain angle

Figure 3 shows the variation in the R-direction of grain angle. The grain was Z-helix. Although the variation pattern was not the W-type, the grain angle increased toward the bark. This variation pattern is called "V-type" in this article.

Figure 4 shows the variation in the R-direction of twist angle by drying. The variation pattern was W-type and the minimum appeared at ±100 mm of the distance from the pith. This ±100 mm corresponded to the value where the annual ring width was the minimum in Fig. 2.

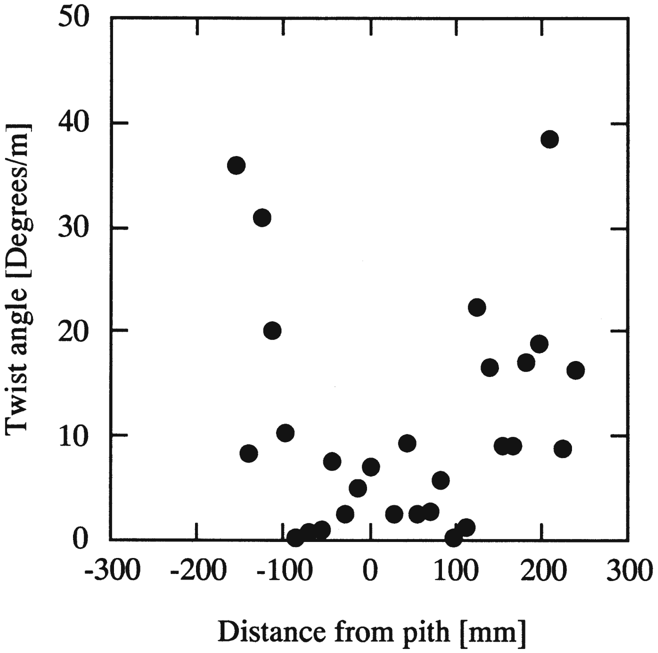

Fig. 4. Radial variation of twist angle by drying

The variation pattern of unit shrinkage in the L-, R-, and T-directions (Fig. 5) did not correspond to that of the annual ring width. Both Young's modulus and strength in static bending increased toward the bark till ±100 mm; past this point, it decreased toward the bark (Fig. 6). This variation pattern corresponded to that of annual ring width and is called "M-type" in this article. Absorbed energy in impact bending also showed an M-type pattern (Fig. 7). Compressive Young's moduli E_{cL}, E_{cR}, and E_{cT}, compressive strength σ_{cL}, and proportional limits P_{cR} and P_{cT} were also of the M-type or V-type (Fig. 8).

Wood properties tend to relate to density. Therefore, relationships of wood properties of PAAm to air-dried density are examined in Table 1. Unit shrinkage in the R-direction, Young's modulus and strength in static bending, compressive Young's modulus, compressive strength, and compressive proportional limit all had high correlations to density. Because specimens for twist angle by drying were warped by drying, their dimensions could not be measured accurately, so their density could not be calculated.

Because variations in the R-direction of many wood properties corresponded to that of annual ring width mentioned above, relationships of wood properties to mean annual ring width are shown in Table 2. The mean annual ring width was obtained by dividing the dimension in the R-direction by the number of annual rings on the RT-plane of each specimen. The twist angle by drying, Young's modulus and strength in static bending, absorbed energy in impact bending, compressive Young's modulus in the L-direction, and compressive strength had high correlations to annual ring width.

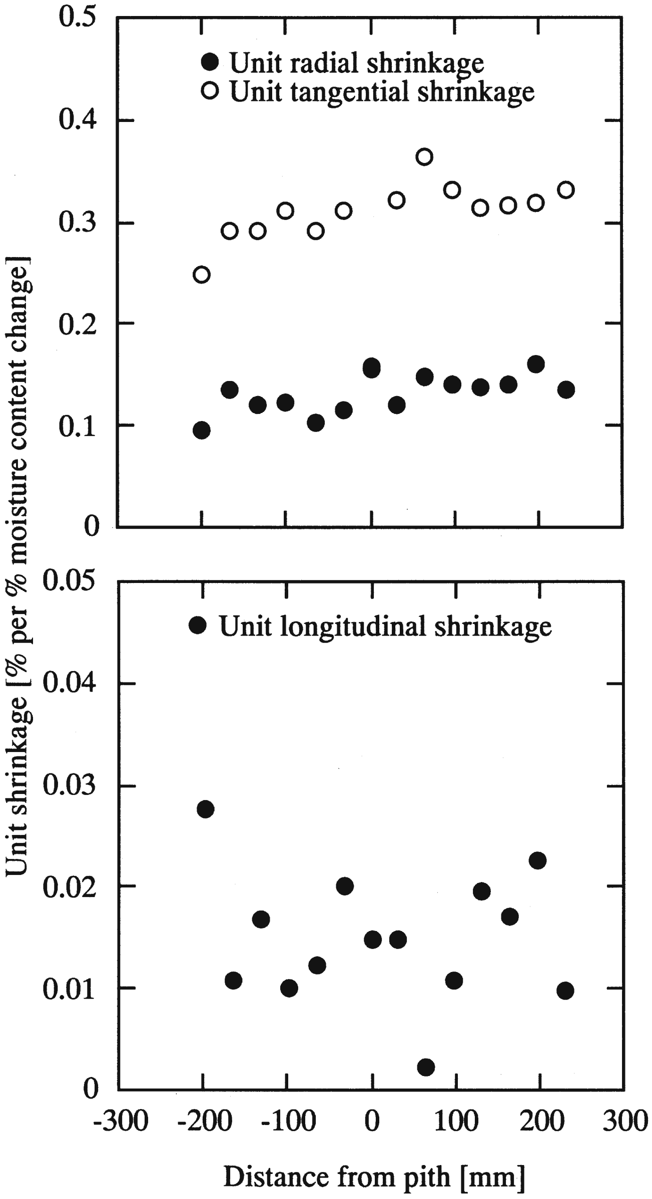

Fig. 5. Radial variation of unit shrinkage. *Top*, radial and tangential shrinkage; *bottom*, longitudinal shrinkage

From the abovementioned results, it is reasonable to conclude that wood of PAAm with widely spaced annual rings has a large grain angle, large twist angle by drying, and low bending properties. The evidence indicates that timber with such properties may not be appropriate for use as construction lumber. If PAAm is afforested artificially in the future for the purposes of lumber production and conservation, the annual rings of logs should not be too widely spaced.

Wood properties of PAAm are listed in Table 3. Comparing them with wood properties of Japanese black pine (*Pinus thunbergii* Parl.), which is another representative pine on Tanega-shima Island,[25] large differences do not exist between these two pines. Hence, it is not surprising

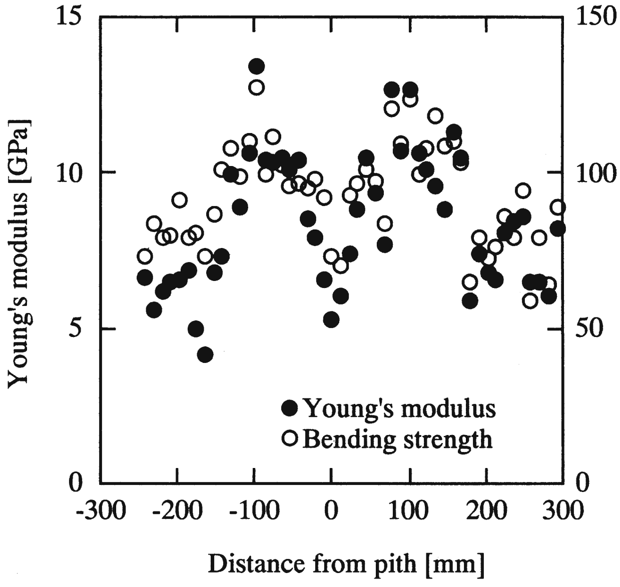

Fig. 6. Radial variation of static bending properties

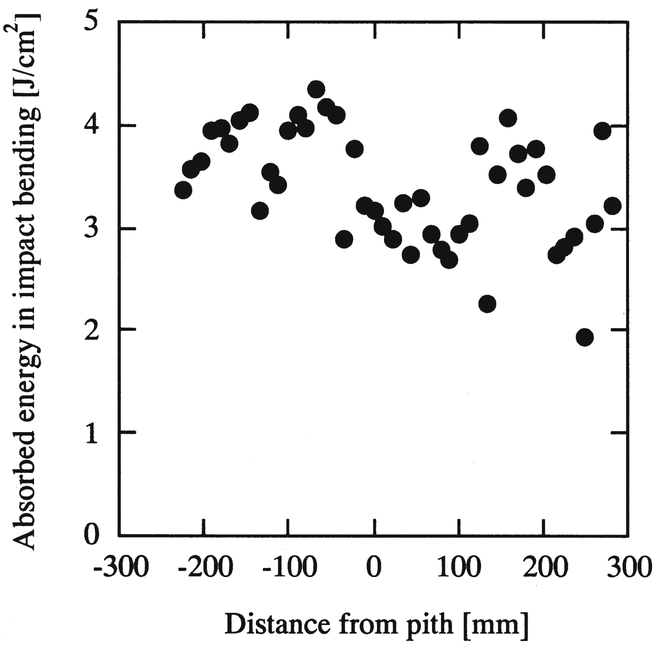

Fig. 7. Radial variation of impact bending properties

that the wood of PAAm has been traditionally used in house construction and other purposes.[3,4,23]

On Tanega-shima Island, it is said that fishing canoes made of PAAm could be used for about 100 years, but those made of Japanese black pine did not last for such a long time.[3,26] Because wood properties of PAAm are similar to those of Japanese black pine, factors such as extractives and resin may be important for the durability of fishing canoes. This is a problem that requires further detailed study.

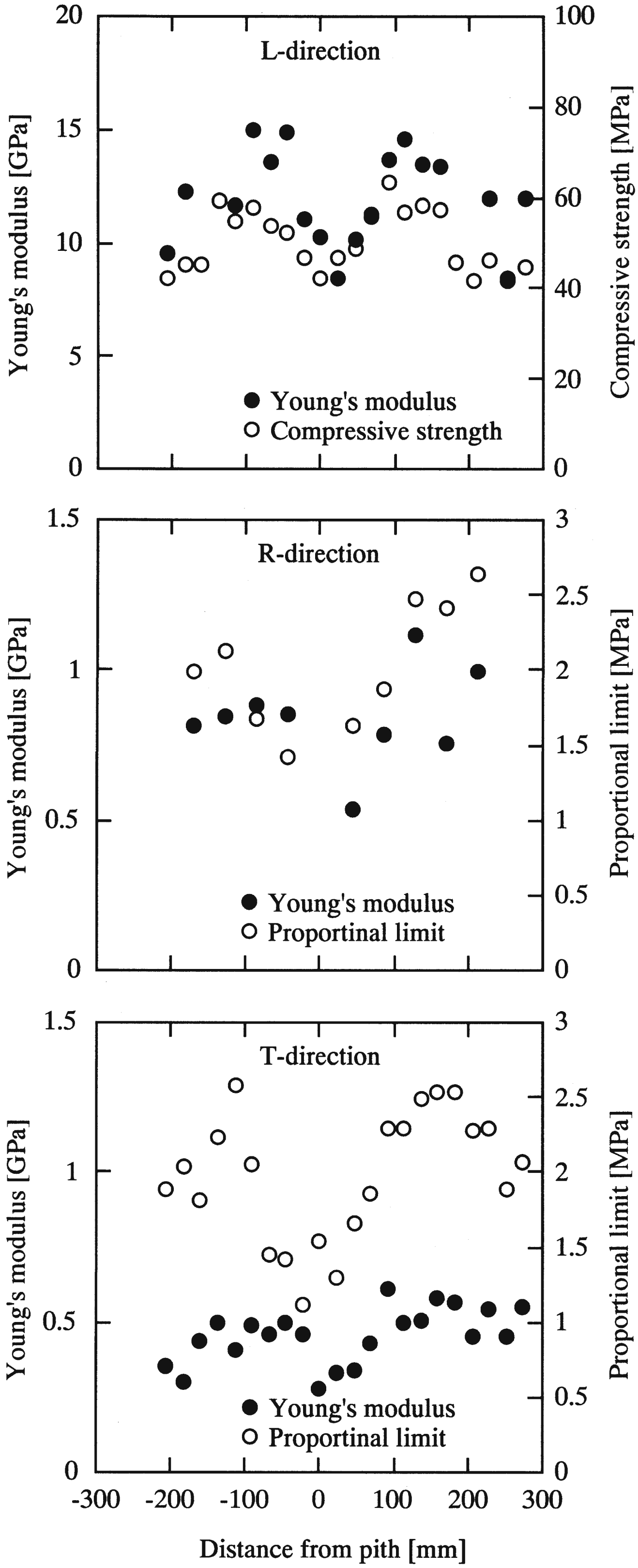

Fig. 8. Radial variation of compressive properties. *Top*, longitudinal direction; *middle*, radial direction; *bottom*, tangential direction

Table 1. Linear relationships of wood properties (*WP*s) with density ρ expressed by the equation of $WP = A\rho + B$

Wood property	A	A units	B	B units	r
δ_L	0.00099	% cm^3 g^{-1}	0.014	%^{a}	0.00561
δ_R	0.28	% cm^3 g^{-1}	–0.019	%^{a}	0.591*
δ_T	0.30	% cm^3 g^{-1}	0.15	%^{a}	0.446
E_{sb}	34.32	GPa cm^3 g^{-1}	–10.45	GPa	0.661**
σ_{sb}	314.83	MPa cm^3 g^{-1}	–82.95	MPa	0.746**
W_{ib}	–2.99	J cm g^{-1}	5.08	J cm^{-2}	0.269
E_{cL}	35.27	GPa cm^3 g^{-1}	–7.64	GPa	0.589*
E_{cR}	2.92	GPa cm^3 g^{-1}	–0.80	GPa	0.707*
E_{cT}	2.36	GPa cm^3 g^{-1}	–0.86	GPa	0.773**
σ_{cL}	133.55	MPa cm^3 g^{-1}	–23.31	MPa	0.706**
P_{cR}	8.35	MPa cm^3 g^{-1}	–2.69	MPa	0.782*
P_{cT}	11.66	MPa cm^3 g^{-1}	–4.53	MPa	0.813**

δ_L, δ_R, δ_T, Unit shrinkage (from air dry to oven dry) in the longitudinal, radial, and tangential directions, respectively; E_{sb}, Young's modulus in static bending; σ_{sb}, static bending strength; W_{ib}, absorbed energy in impact bending; E_{cL}, E_{cR}, E_{cT}, compressive Young's modulus in the longitudinal, radial, and tangential directions, respectively; σ_{cL}, compressive strength; P_{cR}, P_{cT}, compressive proportional limit in the radial and tangential directions, respectively

* $P < 0.05$; ** $P < 0.01$

[a] Percent shrinkage per percent change in moisture content

Table 2. Linear relationships of *WP*s to mean annual ring width b expressed by the equation of $WP = Ab + B$

Wood property	A	A units	B	B units	r
θ	5.9	° m^{-1} mm^{-1}	–8.2	° m^{-1}	0.594**
δ_L	0.0024	% mm^{-1}	0.0057	%^{a}	0.500
δ_R	0.00057	% mm^{-1}	0.13	%^{a}	0.0397
δ_T	–0.0055	% mm^{-1}	0.33	%^{a}	0.270
E_{sb}	–0.54	GPa mm^{-1}	10.63	GPa	0.427**
σ_{sb}	–3.64	MPa mm^{-1}	107.55	MPa	0.388**
W_{ib}	–0.13	J cm^{-2} mm^{-1}	3.9	J cm^{-2}	0.329*
E_{cL}	–1.04	GPa mm^{-1}	15.79	GPa	0.721**
E_{cR}	–0.022	GPa mm^{-1}	0.92	GPa	0.161
E_{cT}	–0.0078	GPa mm^{-1}	0.49	GPa	0.113
σ_{cL}	–3.48	MPa mm^{-1}	63.69	MPa	0.762**
P_{cR}	0.18	MPa mm^{-1}	1.40	MPa	0.507
P_{cT}	–0.044	MPa mm^{-1}	2.15	MPa	0.137

θ, Twist angle

* $P < 0.05$; ** $P < 0.01$

[a] Percent shrinkage per percent change in moisture content

Conclusions

A dead PAAm tree was obtained and various properties of its wood were measured. Results are as follows.

1. Roughly speaking, variations in the R-direction of the grain angle, twist angle by drying, Young's modulus and strength in static bending, absorbed energy in impact bending, compressive Young's modulus, compressive strength, and compressive proportional limit corresponded to the variation of annual ring width.
2. Unit shrinkage in the R-direction, Young's modulus and strength in static bending, compressive Young's modulus, compressive strength, and compressive proportional limit all had high correlations with density.
3. The twist angle by drying, Young's modulus and strength in static bending, absorbed energy in impact bending, compressive Young's modulus in the L-direction, and compressive strength had high correlations with annual ring width.
4. Generally speaking, wood of PAAm with widely spaced annual rings has a large grain angle, large twist angle by drying, and low bending properties. It is possible to say that timber with such properties is not appropriate for use as construction lumber.
5. If PAAm is afforested artificially in the future for the purposes of lumber production, the annual rings of logs should not be too widely spaced.
6. Wood properties of PAAm were similar to those of Japanese black pine.

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Table 3. Wood properties of *Pinus armandii* var. *amamiana*

	ρ (g cm^{-3})	δ_L (%)	δ_R (%)	δ_T (%)	E_{sb} (GPa)	σ_{sb} (MPa)	W_{ib} (J cm^{-2})	E_{cL} (GPa)	E_{cR} (GPa)	E_{cT} (GPa)	σ_{cL} (MPa)	P_{cR} (MPa)	P_{cT} (MPa)	ν_{LR}	ν_{LT}	ν_{RL}	ν_{RT}	ν_{TL}	ν_{TR}
Pinus armandii var. *amamiana*[a]	0.55 (0.063)	0.015 (0.0061)	0.16 (0.018)	0.30 (0.047)	8.37 (2.18)	92.2 (16.2)	3.40 (0.55)	11.08 (2.65)	0.77 (0.27)	0.46 (0.089)	50.39 (6.57)	1.93 (0.47)	1.98 (0.42)	0.50 (0.065)	0.54 (0.068)	0.060 (0.022)	0.76 (0.080)	0.051 (0.023)	0.47 (0.067)
Japanese black pine[b]	0.54 (0.44–0.67)	–	0.20 (0.16–0.24)	0.30 (0.27–0.33)	10.5 (7.5–13.0)	85 (65–110)	5.0 (3.0–8.0)	–	–	–	45 (35–60)	–	–	–	–	–	–	–	–

ν, Poisson's ratio

[a] Data given as means with standard deviations in parentheses

[b] Data derived from Wood Technological Association of Japan[25] and given as means with ranges in parentheses

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