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Tadashi Ohtani · Takao Yakou · Shigeru Kitayama

Effect of annual rings on abrasive wear property of wood

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Abstract In this study we investigated the abrasive wear property of Douglas fir (*Pseudostuga menziesii* Franco) on abrasive paper using test specimens with various dimensions and annual ring widths. The effect of the annual rings on the abrasive wear property of Douglas fir was clarified from the relation with the compression strength of the wood specimens. The dispersion of the wear coefficient, which was calculated as the wear volume divided by the friction distance and the load applied to the friction surface, varied when there were fewer than approximately three annual rings in the specimen, as did the compression strength. As clarified from these results, it was found that the effect of the annual rings on the abrasive wear and compression properties of Douglas fir is closely related to the earlywood/latewood ratio.

Key words Abrasive wear · Annual ring · Compression strength · Wear coefficient · Earlywood and latewood

Introduction

The mechanical and physical properties of wood products are affected by the annual rings when wood is used at designated dimensions. The effect of annual rings has often been discussed in terms of the relation between the number of annual rings and the specimen size. Therefore, the appropriate dimensions of a test specimen has been standardized in some methods for testing wood as described in the Japanese Industrial Standard (JIS).[1] It has also been reported that compression strength changes when there are fewer than two or three annual rings.[2]

As a fundamental testing method for evaluating the wear resistance of materials, the abrasive wear test on abrasive paper has been used.[3–6] It was reported that the wear properties of metal and plastic materials revealed by abrasive wear tests were closely related to the surface hardness of materials, and the material became more difficult to abrade as it became harder.[3,4] We noted earlier that the abrasive wear property of wood was related to the strength of the material. It was also clarified that the wear volume of wood decreases as the yield stress increases during compression.[5,6] Such findings indicate that it is highly likely annual rings have an effect on the abrasive wear property.

In this study, we investigated the abrasive wear property of Douglas fir on abrasive paper using test specimens with different dimensions and annual ring widths. The effect of the annual rings on the abrasive wear property was clarified from the relation with the compression strength of the specimens.

Experimental

Rectangular blocks of Douglas fir (*Pseudostuga menziesii* Franco) in which the interval of the annual rings was almost the same were used as the sample specimens. The physical properties of the Douglas fir used in this experiment are shown in Table 1. Eleven blocks [150(R) × 40(T) × 100(L) mm^3] in which annual ring widths differed were the test specimens.

As shown in Table 1, the average widths (W) of annual rings of the test specimens ranged from 1.6 to 6.8mm. The densities (ρ) ranged from 0.45 to 0.64g/cm^3 and the mois-

T. Ohtani (✉)
Faculty of Science and Engineering, Shimane University, 1060 Nishikawatsucho, Matsue 690-8504, Japan
Tel. +81-852-32-6207; Fax +81-852-32-6123
e-mail: t-ohtani@riko.shimane-u.ac.jp

T. Yakou
Graduate School of Engineering, Yokohama National University, Yokohama 240-8501, Japan

S. Kitayama
Graduate School of Agriculture, Tokyo University of Agriculture and Technology, Fuchu 183-0054, Japan

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Table 1. Douglas fir criteria of properties for the sample specimen

Douglas fir (*P. menziesii* Franco)	Average width of annual rings *W* (mm)	Density *ρ* (g/cm^3)	Moisture content (%)
a	1.6	0.64	7.8
b	2.2	0.59	8.9
c	2.6	0.63	8.9
d	3.1	0.47	8.9
e	3.6	0.55	9.4
f	4.3	0.45	9.2
g	5.5	0.46	9.1
h	6.0	0.46	9.0
i	6.3	0.49	9.4
j	6.7	0.48	9.7
k	6.8	0.45	7.7

ture contents from 7.8% to 9.7%. We used two types of test specimen for which the cross section was set as the friction surface. One type had a constant annual ring width but different cross-sectional areas (A) (3×3, 5×5, 10×10, and $20 \times 20 mm^2$). The other type had a constant cross-sectional area of $10 \times 10 mm^2$ but different annual ring widths.

Abrasive wear tests were performed by sliding the test specimen on a plate.[5] The test specimen was rubbed by abrasive paper on a plate that moved 100mm along a straight line at a speed of 20mm/s. The test specimen was rubbed in one direction on a virgin surface of abrasive paper. The abrasive paper was made of #120 Al_2O_3 abrasive grains (mean abrasive grain size 132μm). The surface pressure (p) applied to the friction surface was 0.1MPa.

Compression tests in the direction parallel to the grain of the wood were performed using a testing machine of the Instron type to examine the compression property of the specimens. The compression test specimen was prepared from the blocks as described in Table 1. The cross-sectional area was the same as that of the abrasive test specimen (i.e., 3×3, 5×5, 10×10, and $20 \times 20 mm^2$). The height of the specimen always had twice the cross-sectional dimension. The cross-head speed during the compression test changed according to the cross-sectional area of the specimen. The nominal strain speed ($\dot{\varepsilon}$) during compression was constant: $\dot{\varepsilon} = 1.7 \times 10^{-4} s^{-1}$.

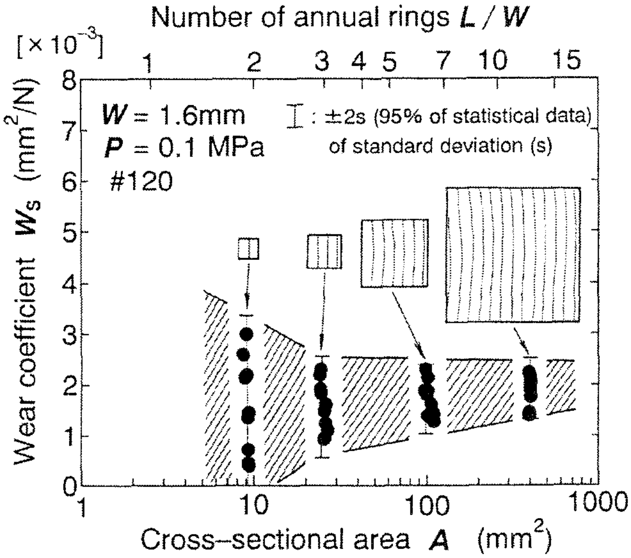

Fig. 1. Relation between the wear coefficient (W_s) and the cross-sectional area (A) in Douglas fir specimen a ($W = 1.6$mm)

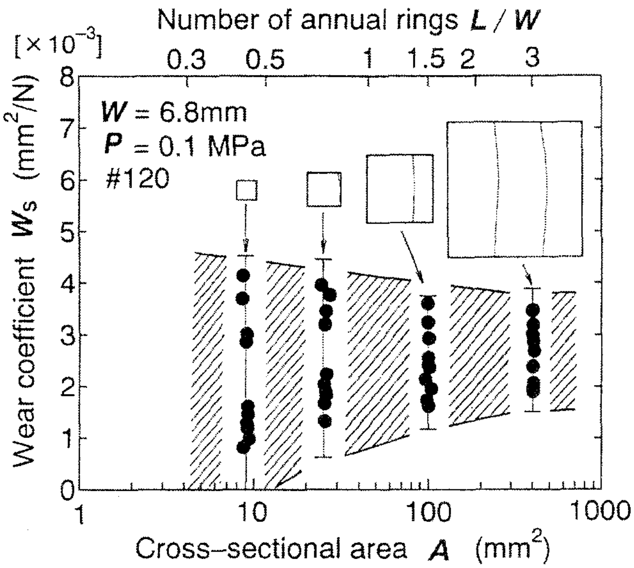

Fig. 2. Relation between the wear coefficient (W_s) and the cross-sectional area (A) in Douglas fir specimen k ($W = 6.8$mm). Refer to Fig. 1 for an explanation of the error bars

Results and discussion

Effect of annual rings on abrasive wear

Figure 1 shows the relation between the wear coefficient (W_s) of Douglas fir specimens with different dimensions and cross-sectional areas (A): ($W = 1.6$mm). W_s was calculated as the wear volume (mm^3) divided by the applied load (N) and friction distance (mm). The error bar in Fig. 1 contains approximately 95% of the statistical data calculated from the standard deviation; and the hatched area is the range of the error bars. The W_s obtained from 10 specimens varies with A, and the dispersion tends to become smaller as A becomes larger. Moreover, the value of W_s is scattered from $0.5 \times 10^{-3} mm^2/N$ to $3 \times 10^{-3} mm^2/N$ when $A = 9 mm^2$ (3×3mm). In Fig. 1, L/W gives the number of annual rings calculated as the length of one side of the compression plane divided by the average width of the annual rings. When the W_s is described in relation to the value of L/W, the dispersion of W_s increases at around $L/W = 2$. In this case, there were fewer than approximately three annual rings in the specimen. Figure 2 shows the relation between W_s and A at $W = 6.8$mm. When the width of the annual rings is greater, the range of dispersion of W_s is minimum at

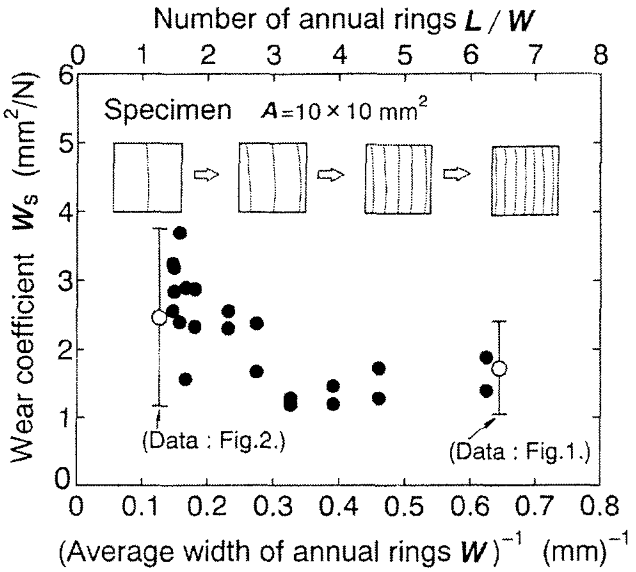

Fig. 3. Relation between the wear coefficient (W_s) in specimens of A = 10 × 10mm^2 and the inverse of the average width of annual rings (W^{-1})

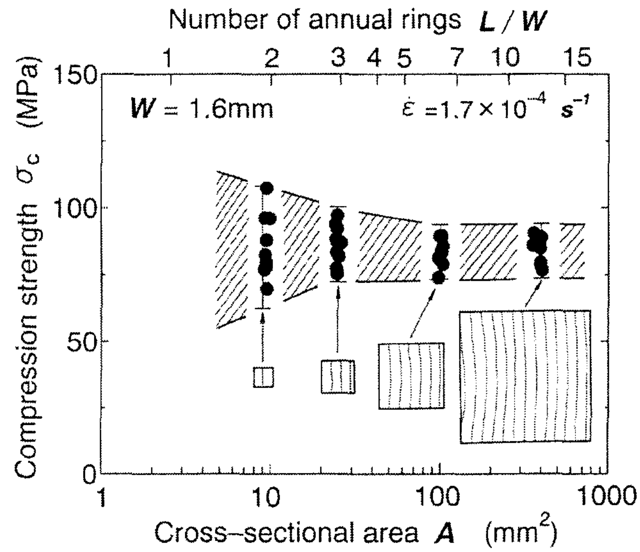

Fig. 4. Relation between the compression strength (σ_c) and the cross-sectional area (A) in Douglas fir specimen a (W = 1.6mm). Refer to Fig. 1 for the explanation of error bars

A = 400mm^2 (20 × 20mm). Moreover, when the W_s is also described in relation to the value of L/W, the dispersion of W_s is smaller when L/W = 3.

Figure 3 shows the relation between W_s at A = 10 × 10mm^2 and the inverse of the average width of the annual rings (W^{-1}). The wear test was performed using two specimens each of samples a to k. As shown in Fig. 3, the value of W_s at W^{-1} of less than approximately 0.3 tends to vary from 2 × 10^{-3} to 4 × 10^{-3}mm^2/N; in the test specimen of the same dimensions in which the width of annual rings differs, the wear coefficient tends to vary when there are fewer than approximately three annual rings in the test specimen. Based on these results, then, it seems that the abrasive wear property of Douglas fir used in this experiment greatly changes when the number of annual rings is more than or less than about three.

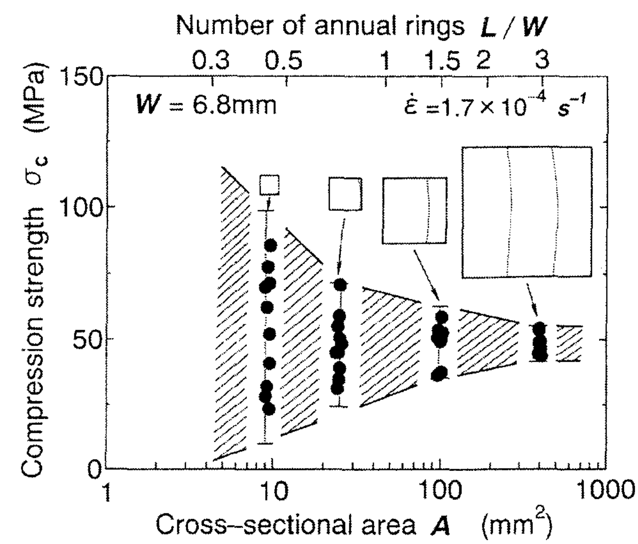

Fig. 5. Relation between the compression strength (σ_c) and the cross-sectional area (A) in Douglas fir sample k (W = 6.8mm). Refer to Fig. 1 for the an explanation of the error bars

Effect of annual rings on compression strength

The action of rubbing the wood specimen on abrasive paper means that the compression force is applied perpendicular to the friction surface. However, it is thought that the wood microstructures in the surface receives a complicated combination of stresses, such as compression, tensile, and shear stresses due to the friction. Therefore, we investigated the effect of the annual rings by focusing on the relation between abrasive wear and compression strength. Here, the compression strength is evaluated parallel to the grain as the strength in the direction of the force applied on the friction surface.

Figures 4 and 5 show the relations between the compression strengths (σ_c) of specimens with different dimensions and cross-sectional areas. As shown in Fig. 4, the value of σ_c obtained from 10 specimens varies with A. The range of dispersion tends to become smaller as the A becomes larger. The value of σ_c varies considerably from 70 to 110MPa when A = 9mm^2 (3 × 3mm), whereas the value of σ_c when A is more than 25mm^2 (5 × 5mm) is between 75 and 90MPa. In contrast, the results in Fig. 5 show that the value of σ_c tends to vary more than that when W is small (W = 1.6mm), as shown in Fig. 4. The range of dispersion of σ_c becomes smaller at around A = 400mm^2 (20 × 20mm). These results indicate that the value of σ_c varies more when the number of annual rings is less than L/W = 2 or 3.

Figure 6 shows the relation between σ_c at A = 10 × 10mm^2 and the inverse of the average width of annual rings (W^{-1}). The value of σ_c at various widths of annual rings tends to vary more when W^{-1} is less than approximately 0.3. The range of dispersion of σ_c is approximately 30–50MPa,

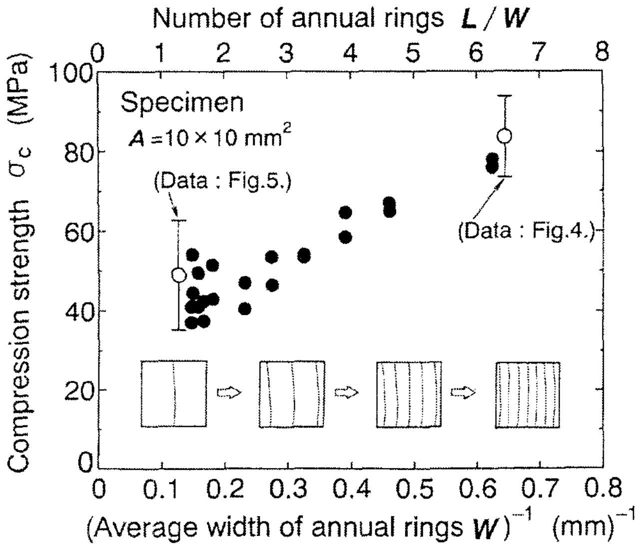

Fig. 6. Relation between the compression strength (σ_c) at $A = 10 \times 10\,mm^2$ and the inverse of the average width of the annual rings (W^{-1})

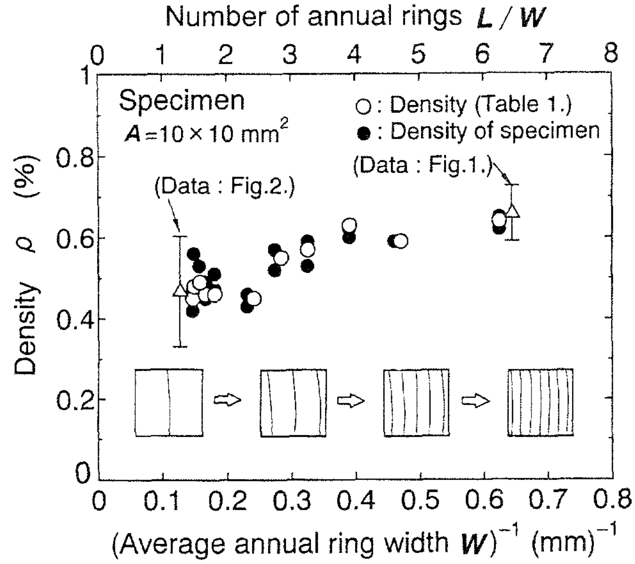

Fig. 7. Relation between the density (ρ) in specimens of $A = 10 \times 10\,mm^2$ and the inverse of the average width of the annual rings (W^{-1})

and the dispersion of σ_c tends to be greater when L/W is less than 3. The compression property of wood also changes significantly when there are fewer than approximately three annual rings.

The above results reveal that the effect of annual rings on the abrasive wear property is closely related to their effect on the compression strength of wood. The effect of annual rings on both characteristics is marked when there are fewer than approximately three annual rings in the specimen.

Effect of annual rings on abrasive wear property

Because the abrasive wear and compression strength of wood are influenced by the void volume of wood, the compression strength is higher and the wear volume is smaller as the density of wood increases.[7] In the following discussion, the effect of the annual rings on the abrasive wear property is investigated from the viewpoint of its relation with the density of wood.

Figure 7 shows the relation between the density (ρ) of the worn specimen of $A = 10 \times 10\,mm^2$ and the inverse of the average width of the annual rings (W^{-1}). The density of each specimen of $A = 10 \times 10\,mm^2$ tends to vary when W^{-1} is less than 0.4. Moreover, the density of these specimens varies more than that of the 11 blocks listed in Table 1. However, the two densities are almost the same when W^{-1} is more than 0.4. Based on this result, it is thought that each specimen used in this experiment has distinct properties.

Figure 8 shows the measured densities of earlywood and latewood, which were used to investigate the properties of the specimens. Because the distribution of the densities of earlywood and latewood is different for each wood species, in this study the hardness of each midsection of the earlywood and latewood was measured with a durometer hard-

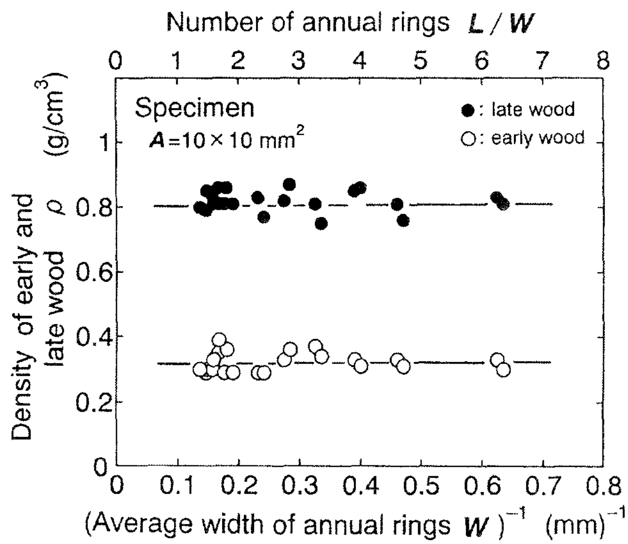

Fig. 8. Relation between the density (ρ) of earlywood and latewood in specimens of $A = 10 \times 10\,mm^2$ and the inverse of the average width of annual rings (W^{-1})

ness tester. Here, as the value of durometer hardness was clarified to relate proportionally to the density, each density of the earlywood and latewood was estimated based on the hardness.[8] As shown in Fig. 8, the densities of the earlywood and latewood are constant: approximately $\rho = 0.3\,g/cm^3$ for earlywood and $0.8\,g/cm^3$ for latewood. Based on this result, we concluded that the specimens used for this experiment had no difference in the densities of the earlywood and latewood. We then used the latewood (R_{late})/W^{-1} ratio to measure the area ratio of earlywood and latewood on the worn surface, as shown in Fig. 9. Note that R_{late} tends to vary from 20% to 40% when there are fewer than approximately three annual rings. Because changes in the dispersion of R_{late} are similar to those in the density of the specimen, as shown in Fig. 7, it is thought that the effect of

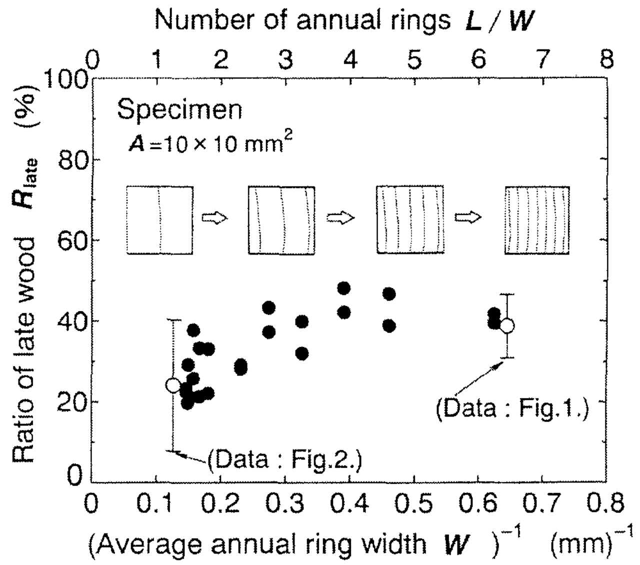

Fig. 9. Relation between the ratio of latewood (R_{late}) in specimens of $A = 10 \times 10\,mm^2$ and the inverse of the average width of annual rings (W^{-1})

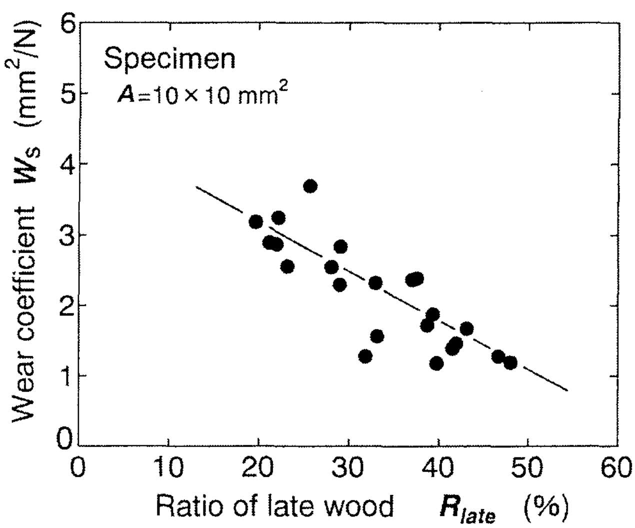

Fig. 10. Relation between the wear coefficient (W_s) in specimens of $A = 10 \times 10\,mm^2$ and the latewood ratio (R_{late})

annual rings on abrasive wear and compression properties is related to the earlywood/latewood ratio in the specimens. The relations of R_{late} to the wear coefficient (W_s) in Fig. 3 and the compression strength (σ_c) in Fig. 6 are shown in Figs. 10 and 11, respectively. W_s tends to be smaller with increasing R_{late}. In contrast, σ_c tends to be greater with increasing R_{late}; the change in W_s corresponds 1:1 with that of σ_c.

Consequently, we found that the amount of wear during abrasion is related linearly to the amount of compression on the material's surface. Moreover, the effect of the annual rings on the abrasive wear and compression properties when there are fewer or more than about three annual rings is closely related to the earlywood/latewood ratio.

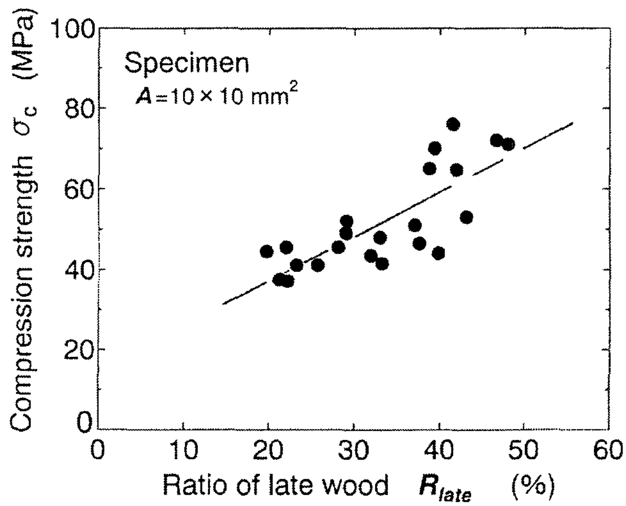

Fig. 11. Relation between the compression strength (σ_c) at $A = 10 \times 10\,mm^2$ and the latewood ratio (R_{late})

Conclusions

The effect of annual rings on the abrasive wear property of Douglas fir was investigated using various specimens with different dimensions and annual ring widths. The results were as follows.

1. In regard to the abrasive wear property of Douglas fir, the dispersion of the wear coefficient increased in specimens with various dimensions and constant annual ring widths when there were fewer than approximately three annual rings in the specimen.
2. Regarding the abrasive wear property of Douglas fir, in specimens with the same dimensions but different annual ring widths, the dispersion of the wear coefficient increased when there were fewer than approximately three annual rings.
3. Changes in the compression strength of Douglas fir were similar to those of the abrasive wear property when there were fewer than approximately three annual rings.
4. The amount of wear during abrasive wear was related linearly to the compression strength on the material's surface; and the effect of the annual rings on the abrasive wear and compression properties was closely related to the earlywood/latewood ratio.

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