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Abrasive wear properties of compressed sugi wood

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Abstract We examined the abrasive wear properties and the effect of abrasive grain size on the rate of wear when sugi wood (*Cryptomeria japonica* D.Don), compressed to various densities, was rubbed with abrasive paper. The results showed that the wear resistance of compressed wood increased linearly with the increased compression ratio; and under the condition of a low compression ratio it tended to be higher in comparison with the strength of compressed wood. The critical grain size effect, which can be witnessed during the abrasive wear of metals and plastics, was seen when low pressure was applied to the abrasive material. At higher pressures, the wear rate of the compressed wood increased with grain size, but the critical grain size effect was not observed. The pressure required to create the critical grain size effect was found to be higher than that needed for other types of uncompressed wood with the same yield properties.

Key words Compressed wood · Abrasive wear · Grain size effect · Yield stress · Compression ratio

Introduction

Abrasive wear of wood occurs when the material is brought into contact with rugged or abrasive particles. One method for examining this phenomenon is to rub a sample of the material with abrasive paper and observe the results. However, it can be difficult to abrade a sample if it has high density and yield stress.[1] In addition, the size of the rugged or abrasive particles affects the rate of abrasion. Generally, the critical grain size effect, which indicates that the wear rate is constant for a range of grain diameters, is observed when metals and plastics are rubbed with abrasive paper or abrasive particles.[2,3] It has been suggested that this constant wear rate is proportional to the relation between the indented depth and the number of abrasive grains in contact with the surface.[4] However, the rate of wear of woods increases with grain size, so the critical grain size effect is not witnessed.[1,4] It is suggested that the critical grain size effect is not observed during the abrasive wear of wood, which is related to cell structure and microbuckling of the wood cell walls.[4] This phenomenon makes sanding and polishing wood easier than metals and plastics but decreases the wear resistance of the material.

High strength and wear-resistant wood is produced by compressing the timber at high temperatures, thereby intentionally decreasing the void volumes. This is done by first softening the wood and then compressing it with heat and steam. The use of compressed sugi wood is proposed for flooring materials, where high wear resistance is required. The problems of dimensional stability for such practical applications of compressed sugi wood have already been studied.[5,6] However, it is important to examine not only the problems of dimensional stability but also the effect of intentionally reducing the void volume. Therefore, in this study we examined the abrasive wear properties of various densities of compressed sugi wood and investigated the effect of grain size on the abrasive wear rate.

Materials and methods

A square sample of sugi wood (*Cryptomeria japonica* D.Don) with a density (ρ) of 0.36g/cm^3, an average annual ring width of 7.4mm, and a moisture content of 10.3% was selected for the study. The sugi wood (thickness 15mm) was compressed at a temperature of 180°C using a heated roller press. The timber of sugi wood was compressed in a direc-

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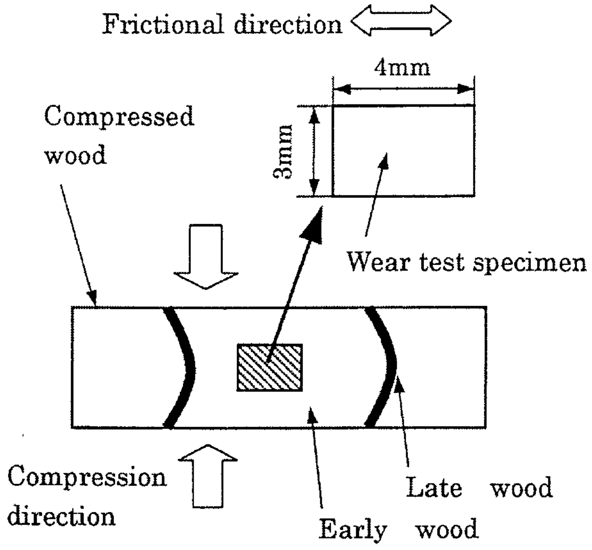

Fig. 1. Wear test specimen sampled from compressed wood

Table 1. Properties of the test specimens used for the experiment

Specimen (*Cryptomeria japonica* D.Don)	Compression ratio *CR* (%)	Density ρ(g/cm^3)
Wood$_{\mathrm{CR=0\%}}$	0	0.23
Wood$_{\mathrm{CR=38\%}}$	38	0.37
Wood$_{\mathrm{CR=63\%}}$	63	0.62
Wood$_{\mathrm{CR=72\%}}$	72	0.82
Wood$_{\mathrm{CR=77\%}}$	77	0.98

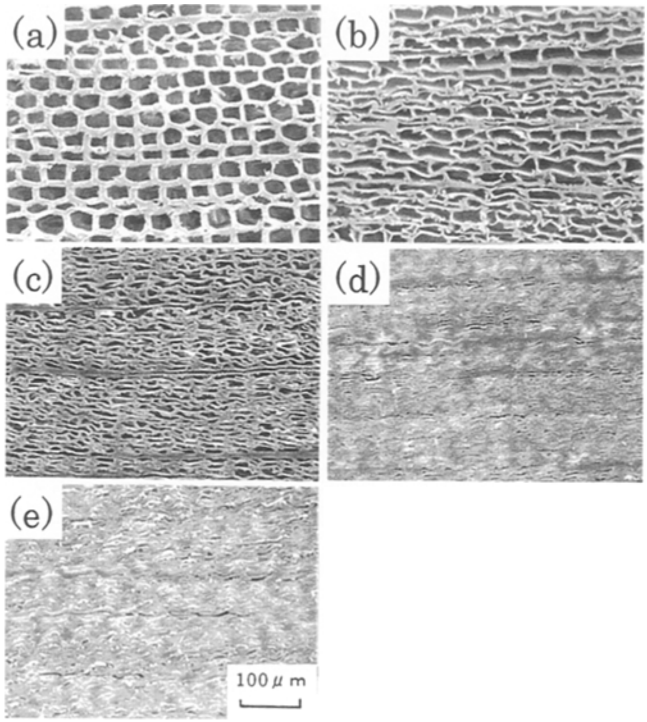

Fig. 2. Scanning electron micrograph of a cross section of the test specimens. Densities in (**a**) to (**e**) are 0.23, 0.37, 0.62, 0.82, and 0.98 g/cm^3, respectively

tion tangential to the annual rings. Each pass through the press compressed the sample by 3 mm. As shown in Fig. 1, the wear test specimen was sampled from earlywood, which is known to exhibit low wear resistance properties. The test specimen was 3 mm (width) × 4 mm (length) × 20 mm (height), and a cross section (3 × 4 mm) of the test specimen was used as the friction surface in the wear resistance tests. The test specimen was rubbed in a direction perpendicular to the compression direction. Table 1 shows the properties of the wear test specimens. The compression ratios *CR* (%) listed in Table 1 were calculated according to the difference in the compressed and uncompressed weights of the test specimens. The density (ρ) in the test specimen of uncompressed sugi wood (wood$_{CR=0\%}$) was 0.23 g/cm^3, and ρ in the compressed wood (from wood$_{CR=38\%}$ to wood$_{CR=77\%}$) was 0.37–0.98 g/cm^3. Figure 2 shows images of the test samples captured using a scanning electron micrograph. These images indicate that the void volume in the compressed wood decreased as the *CR* increased (Fig. 2b–e). Moreover, they show that the structure of the test specimens was compressed homogeneously.

The abrasive wear test was performed according to the following method. The abrasive paper was fixed on a moving plate, and vertical pressure was applied to the test specimen.[7] The test specimen was rubbed in a unidirectional manner over a distance of 100 mm with a sheet of abrasive paper, with mean abrasive grain sizes of 40 μm (#400) to 180 μm (#80). This was repeated six times using a new sheet of abrasive paper for each test.

Results and discussion

Compression properties of compressed sugi wood

Before examining abrasive wear properties of the compressed wood, a compression test was performed on the test specimens listed in Table 1. Figure 3 shows a plot of the nominal stress (σ) versus nominal plastic strain (ε) curves for the test specimens. The compression test was performed in the direction perpendicular to the friction surface. The initial strain speed of compression was $4.2 \times 10^{-4}\mathrm{s}^{-1}$. Among the test samples, σ reaches a maximum with an increase in ε and decreases gradually. Thus, when the maximum stress is defined as the yield stress (σ_y), σ_y increased with the density of compressed wood. Figure 4 shows the relation between σ_y, ρ, and *CR*. The value of σ_y increases gradually until the *CR* is 40% approximately and increases rapidly after the *CR* exceeds 40%. This result indicates that σ_y increases exponentially with increases in *CR*. The change of σ_y shows a tendency similar to that of ρ, as shown in Fig. 4. Based on this result it is concluded that the strength of compressed sugi wood used for this experiment improves when compared with sugi wood (wood$_{CR=0\%}$).

Abrasive wear properties of compressed sugi wood

Figure 5 shows the relation between wear volume (W) and sliding distance (L) when the test specimen was rubbed with

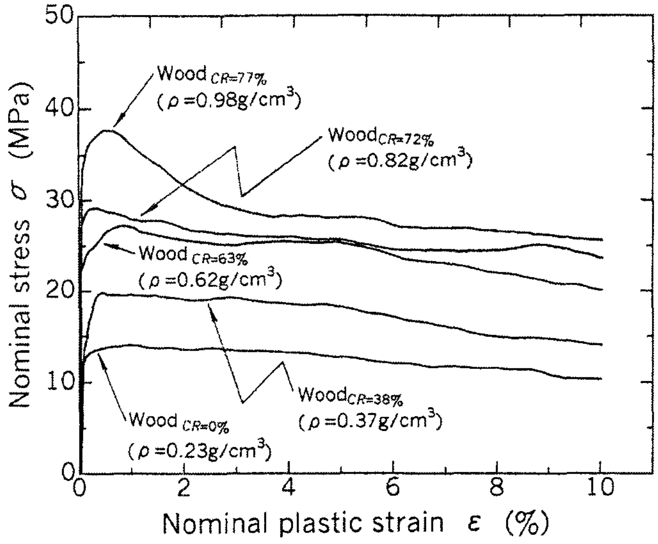

Fig. 3. Nominal stress (σ) versus the nominal plastic strain (ε) curve

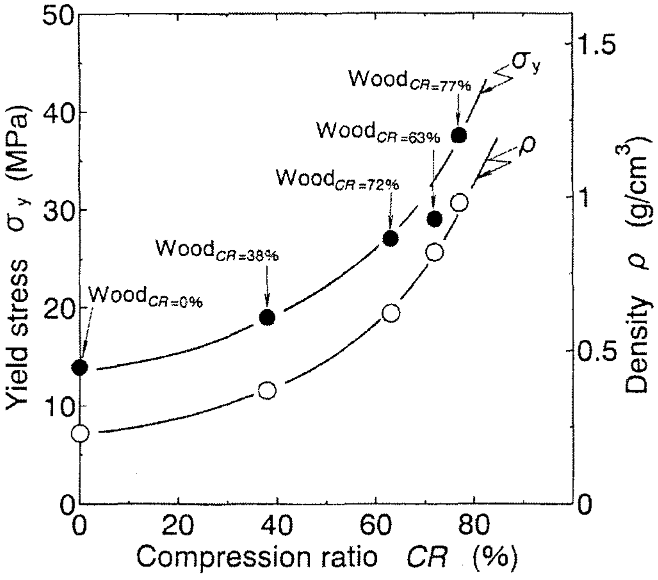

Fig. 4. Relation between the yield stress (σ_y), density (ρ), and compression ratio (CR)

abrasive paper of $\bar{d} = 400\mu m$ (#400) under a pressure P of 0.04 MPa. In the grade of abrasive, W increases linearly with increases in L and decreases as ρ increases. Because W was found to increase linearly with increases in L, the wear rate ($\dot{W}$), defined as a wear volume per unit area, was calculated. Here $\dot{W}$ was calculated by dividing W by the surface area when the test specimen was rubbed with L at 600 mm.[8] The value of $\dot{W}$ was recalculated and represented as a wear rate of L equaling 100 mm. Figure 6 shows the relation between $\dot{W}$ and CR. The value of $\dot{W}$ decreases almost linearly with increases in CR when the test specimen is rubbed on applied pressures P of 0.04 and 0.12 MPa. This result indicates that $\dot{W}$ decreases consistently with the change in CR, although σ_y and ρ, as shown in Fig. 4, increases exponentially with increases in CR.

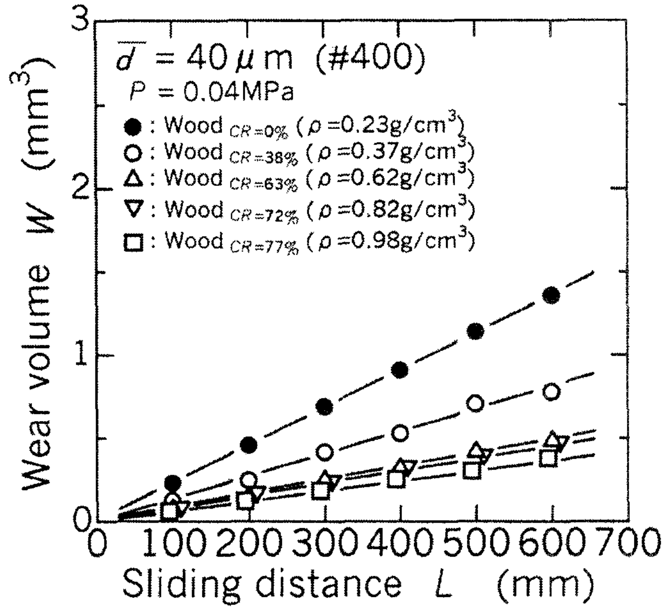

Fig. 5. Relation between the wear volume (W) and the sliding distance (L)

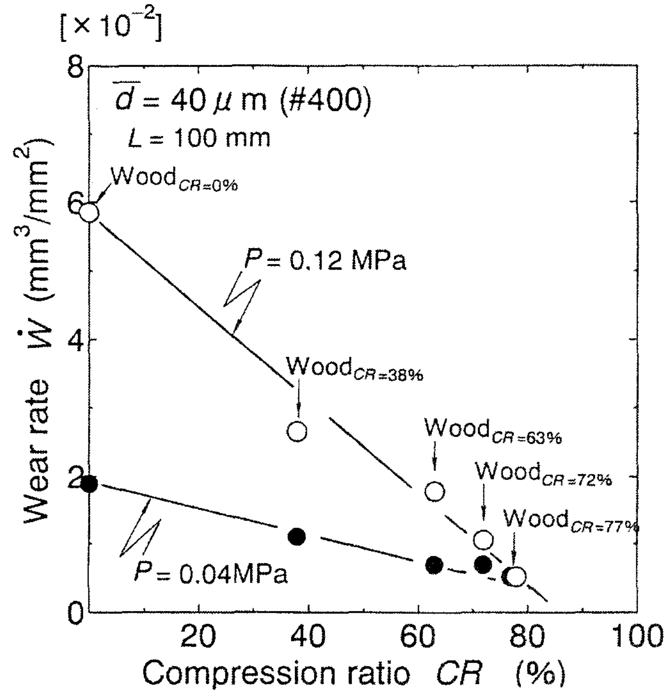

Fig. 6. Relation between the wear rate ($\dot{W}$) and the compression ratio

Figure 7 shows the relation between wear resistance (WR) and CR. The value of WR was calculated according to the following equation.[8]

$$\%WR = \left(\frac{\dot{W}_{CR=0\%} - \dot{W}_{CR=x\%}}{\dot{W}_{CR=0\%}} \right) \times 100$$

As shown in Fig. 7, WR increases approximately linearly with increases in CR on applied pressures P of 0.04 and

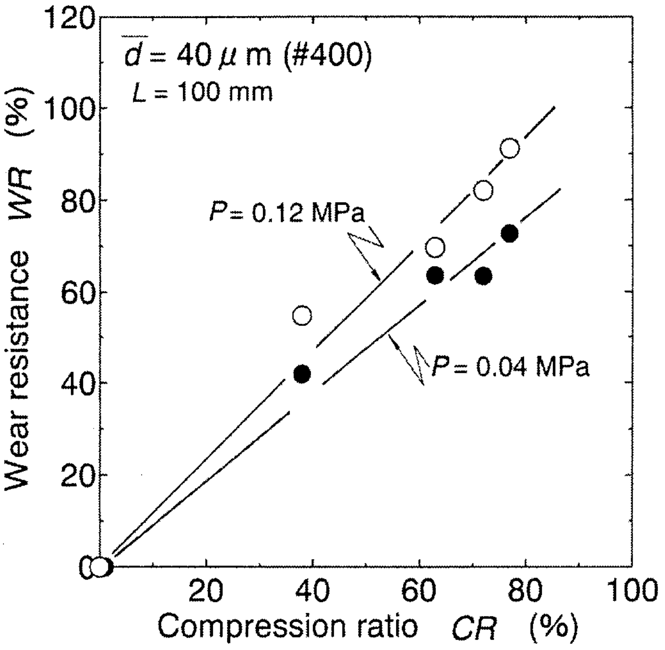

Fig. 7. Relation between wear resistance (WR) and the compression ratio

0.12 MPa. The change in WR does not correspond to that of σ_y, as shown in Fig. 4. Based on this result, it is found that the wear resistance under the condition of a low compression ratio tends to be higher than that of the strength of compressed wood.

Appearance of the critical grain size effect during abrasive wear

To examine the effect of grain size on the rate of abrasive wear, Fig. 8 shows the relation between $\dot{W}$ and the mean abrasive grain size $\bar{d}$ when the sugi wood (wood$_{CR=0\%}$) is rubbed with different grades of abrasive paper. Under a small applied pressure (0.01 MPa), $\dot{W}$ increases with $\bar{d}$ until $\bar{d}$ = 80 μm, after which $\dot{W}$ remains constant. This result indicates that the critical grain size effect is observed. However, at higher applied pressures (0.02–0.04 MPa), $\dot{W}$ increases slightly when $\bar{d}$ is more than 80 μm, indicating that the critical grain size effect is partly observed. Moreover, when the applied pressure is increased to 0.08 MPa, $\dot{W}$ increases linearly with $\bar{d}$ (i.e., the critical grain size effect is not observed). It is therefore concluded that there are three observable regions of grain size effect: Type I region is where the critical grain size effect is witnessed; type II region is one where the critical grain size effect is partially witnessed; and type III region is where the critical grain size effect is not observed.

Figure 9 shows the results of $\dot{W}$ and $\bar{d}$ when the test was performed on a sample of compressed wood (wood$_{CR=38\%}$) with a density ρ of 0.37 g/cm^3. Under low pressures (0.02 MPa), the critical grain size effect is observed (type I region). When the applied pressure is 0.04 or 0.08 MPa, a type II region is observed. When the pressure is increased to

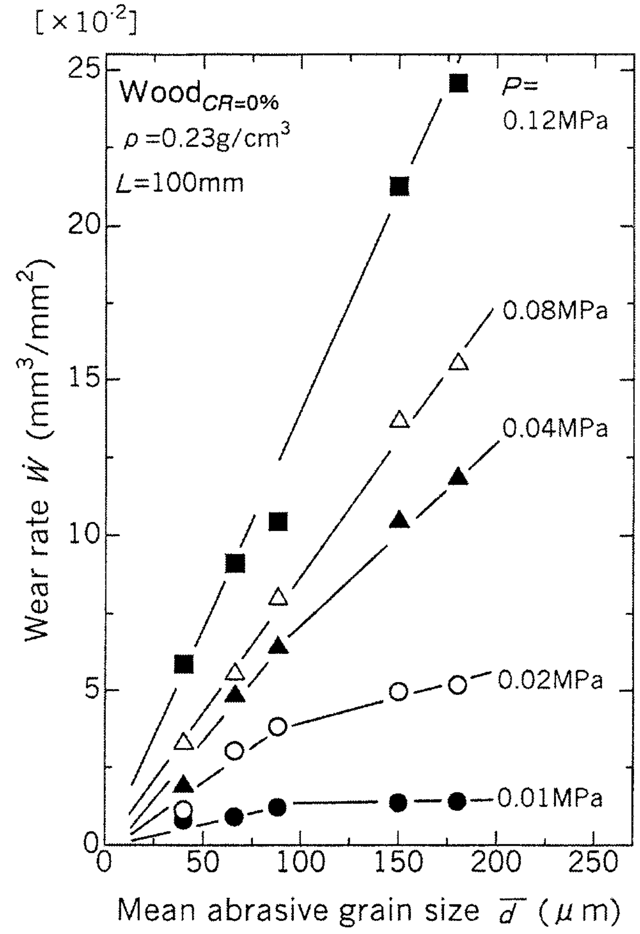

Fig. 8. Relation between the wear rate ($\dot{W}$) and the mean abrasive grain size ($\bar{d}$) on wood$_{CR=0\%}$

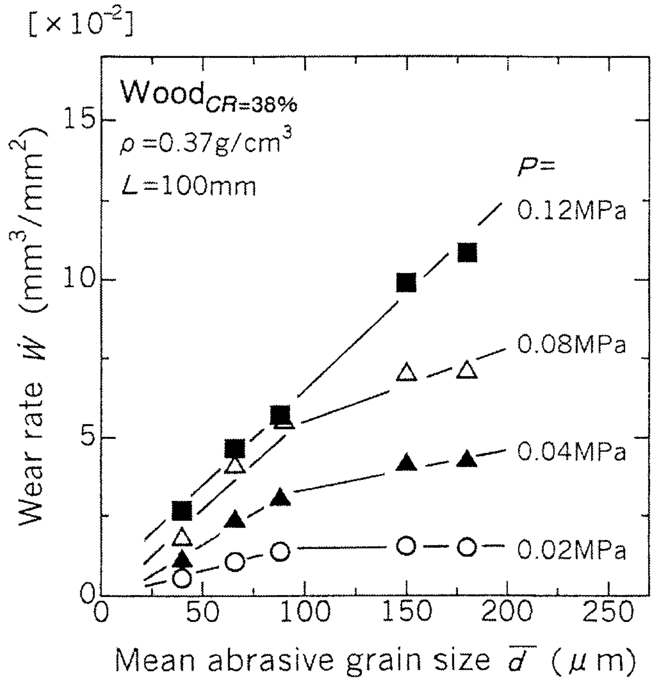

Fig. 9. Relation between the wear rate ($\dot{W}$) and the mean abrasive grain size ($\bar{d}$) on wood$_{CR=38\%}$

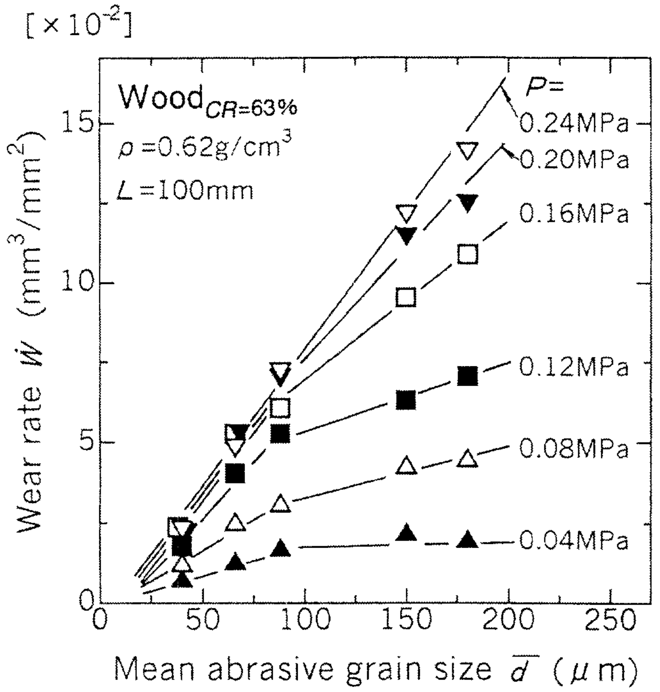

Fig. 10. Relation between the wear rate ($\dot{W}$) and the mean abrasive grain size ($\bar{d}$) on wood$_{CR=63\%}$

0.12MPa, type III regional properties are witnessed. Furthermore, as shown in Fig. 10, when the test is repeated on a sample of wood (wood$_{CR=63\%}$) with a higher density (0.62 g/cm^3), similar results are observed. It is found that a type III result is recorded only when the applied pressure is increased to 0.24MPa. This result suggests that the boundary pressure between type II and III increases with density.

For examining the conditions needed to observe the critical grain size effect, Fig. 11 shows the relation between P and σ_y. The result indicates that the boundary pressures between type I, II, and III regions increase exponentially with σ_y increases. The continuous lines in Fig. 11 represent the appearance conditions of the critical grain size on the other types of wood as already reported.[1] Here, the continuous lines are the results of reanalyzing the data already reported by separating type I from type III. In comparison with the other wood samples, the I–II and II–III boundary lines (dotted lines) for compressed sugi wood are higher. Especially, type II region is much larger than that of wood as the σ_y increases. This indicates that the appearance of the critical grain size effect is maintained in compressed sugi wood until greater pressures are applied. The reason for this result is thought to be that the sugi wood is compressed in one direction, so the shape deformation of the cell structure, as shown in Fig. 1, affects the appearance conditions of the critical grain size effect. This means that the compressed wood has higher wear resistance properties than the other types of wood.

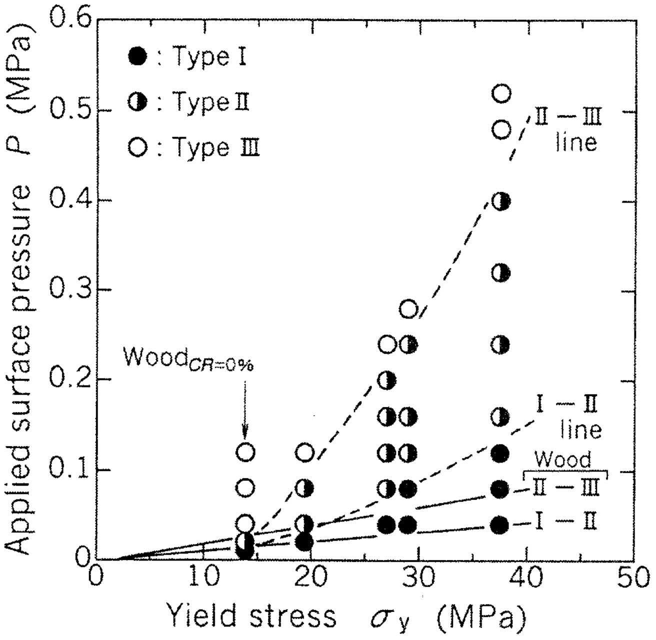

Fig. 11. Relation between the applied surface pressure (P) and the yield stress (σ_y)

Conclusions

We investigated the abrasive wear properties of various densities of compressed sugi wood. The following results were obtained.

1. The yield stress of compressed sugi wood increased exponentially with increases in the compression ratio. The tendency was similar to the change in density.
2. Wear resistance increased linearly with increases in the compression ratio. With a low compression ratio it tended to be higher than that of the strength of compressed wood.
3. The appearance conditions of the critical grain size effect in compressed wood could be grouped into three regions.
4. The boundary pressures between type I, II, and III regions of the critical grain size effect on compressed sugi wood were greater than that of wood; that is, the critical grain size effect was observed on compressed wood at higher pressures.

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