COMPRESSION OF WOOD WITH SUPERIMPOSED SMALL SINUSOIDAL OSCILLATIONS. PART I. ROOM TEMPERATURE

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ABSTRACT

The changes occurring in wood when it is subjected to compression straining in well-defined directions have been studied. The straining has also included dynamic oscillations at frequencies up to 84 Hz.

The changes occurring in the wood have been determined by measurement of the resulting permanent strain of the wood specimens. Fiber damage has been evaluated by measuring the intrinsic viscosity of the pulp after a standardized sulfite delignification. Some microscopic examinations were also carried out.

The compressions were carried out either parallel to or perpendicular to the grain on air-dry or water-saturated specimens. The energy consumption during the compression treatments has also been considered.

Keywords: Compression, compression damage, fiber damage, permanent strain, pulp viscosity, wood.

INTRODUCTION

In a previous study (Winter et al. 1984), the disintegration of wood chips in a refiner was studied in order to determine the conditions that minimize the extent of fiber damage. A substantial degree of fiber damage was, however, obtained even under very mild conditions, i.e., at high temperature and at low energy input. This indicates the disadvantages of using a refiner to accomplish disintegration. Furthermore, the extremely complicated situation in a refiner makes it difficult to unravel the relationships between stresses, fiber orientation, and resultant fiber damage.

The present studies were initiated in the hope of finding mechanical treatments that lead to less fiber damage during disintegration. Wood is known to be sensitive to compressive stresses, and since these are probably important for the mechanical breakdown of wood, the studies were concentrated on the effects of compression

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straining. The studies were performed under dynamic conditions by superimposing small oscillations from different prestraining levels.

Since the mechanical behavior of wood, as in all viscoelastic materials, is time-dependent, the breakdown of wood in high-speed processes such as refining is probably completely different from the breakdown under static conditions. The breakdown of wood under static compression has been studied in several investigations (Bienfait 1926; Dinwoodie 1968; Frey-Wyssling 1953; Hartler 1969; Hartler and LéMon 1969; Keith 1971; Robinson 1920; Scurfield et al. 1972; Wardrop and Addo-Ashong 1963), and the effects on the resultant pulp quality have also been studied (Bildt 1938; Green and Yorston 1939, 1940; Hartler 1963; Hartler et al. 1963; Rys et al. 1952; Stone and Nickerson 1958, 1961). Dynamic conditions have, however, only been used in a limited number of investigations (Gillwald 1961; Rose 1965; Salmén 1982) in which the mechanical fatigue behavior of wood under oscillating stress conditions was studied. The effects on the modulus of elasticity (Gillwald 1961; Rose 1965; Salmén 1982), on the breaking strength (Gillwald 1961; Rose 1965), and on the creeping behavior (Gillwald 1961; Rose 1965) of wood were evaluated. Salmén used the change in modulus of elasticity of the wood to reveal structural changes within the fibers, but contributions from structural changes in the middle lamella were not considered. Höglund et al. (1976) proposed the existence of a relationship between a viscoelastic property of wood and structural changes in the fibers at higher stresses.

In the above-mentioned dynamic investigations, no measurements were made of the structural changes in the fibers themselves. In the present study, structural changes in the fibers were assessed by measuring the viscosity of the pulp after a standardized delignification. This delignification serves to develop the latent fiber damage. The total final permanent strain in the wood, which involves permanent deformation in both the middle lamella and the fiber walls, was also determined. Together, these two parameters (viscosity and permanent strain) give information concerning qualitative changes due to structural deformation. With the aim of subdividing wood into physically undamaged fibers, high permanent strain at preserved viscosity would be desirable. In some cases, structural fiber changes under different compression conditions were studied by polarized light microscopy.

Dynamic conditions were approached by superimposing small sinusoidal strain oscillations on a compression strain. The effects of the degree of compression straining, the frequency, the amplitude of the oscillations, and the time of treatment under a constant compressive strain could thus be determined. The results can also be expected to be influenced by the moisture content, the temperature, and the orientation of the wood. In this study, air-dry and water-saturated specimens, compressed parallel to and perpendicular to the grain, were compared. The effects of temperature will be reported in a second paper (Winter 1984).

EXPERIMENTAL

Test material

Experiments were made with Norway spruce (*Picea abies* (L.) Karst.). A 76-year-old tree grown in the center of Sweden was selected for the studies. The tree was sawn perpendicular to the stem, and discs about 50 mm thick were obtained.

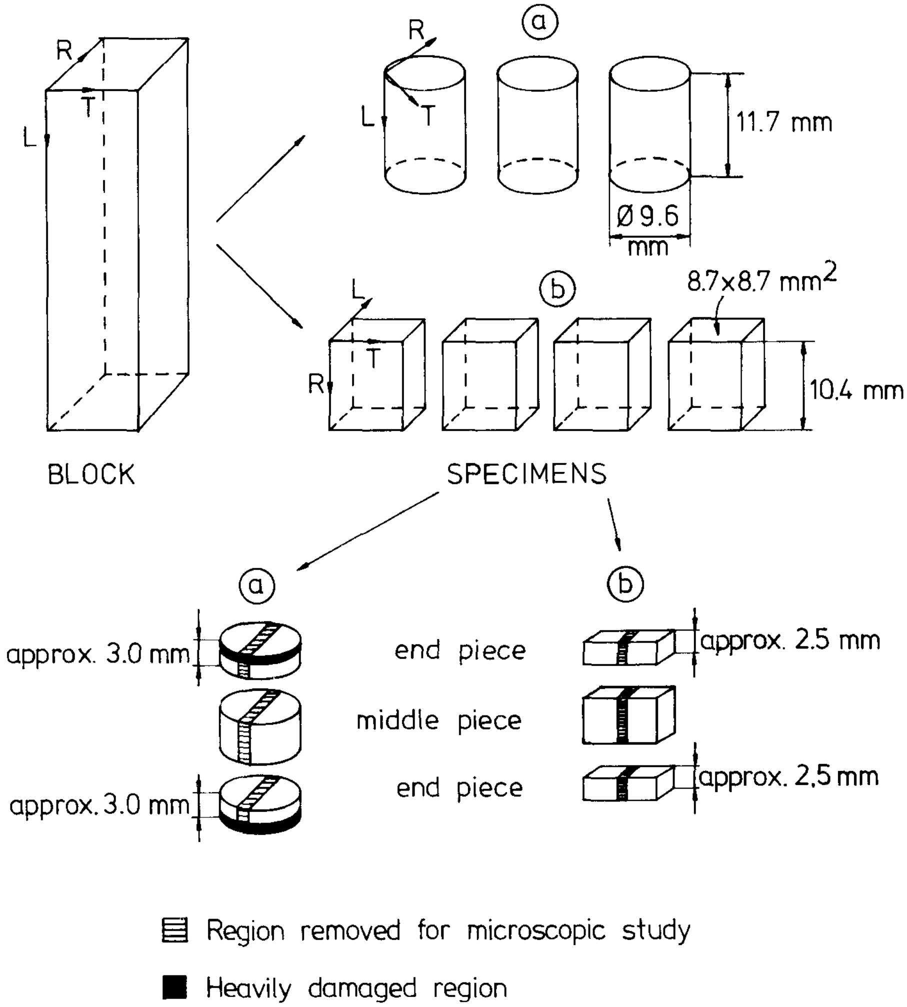

FIG. 1. Preparation and subdivision into pieces of specimens used in compression parallel to the grain (a) and perpendicular to the grain (b).

The bark and the main portion of the heartwood were removed, and the discs were then split into four pieces and carefully dried.

The growth was most uniform between the 49th and 56th annual rings, with a constant width of about 1.76 mm per annual ring, and this interval was chosen for specimen preparation. From blocks the specimens were prepared according to Fig. 1. The cylindrical form was obtained using a sharply edged pipe and was chosen to avoid edge effects that otherwise occur. For compression experiments perpendicular to the grain, four rectangular (parallelepipedal) specimens (including one reference specimen) were used (Fig. 1).

Length, density, and cross-sectional area of the specimens were determined after conditioning at 23 C and 50% RH. The density of the specimens varied between 350 and 400 kg/m^3, and the difference in density between specimens from the same block was less than 6 kg/m^3. The average density of all specimens

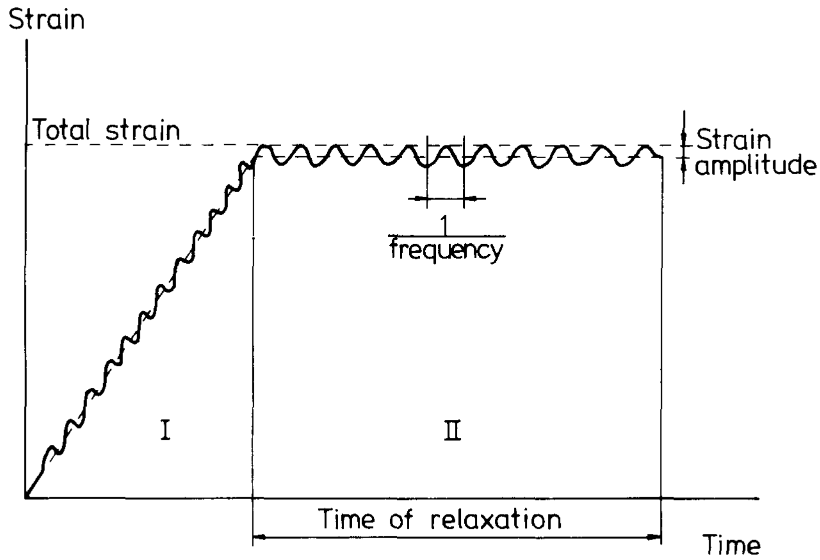

FIG. 2. Compression with superimposed small sinusoidal oscillations. I. Compression period. II. Relaxation period.

was 366 kg/m^3. In compression experiments parallel to the grain, the average length of the specimens was 11.7 mm and the average diameter 9.6 mm. In compression experiments perpendicular to the grain, the average length was 10.4 mm and the cross-sectional area 75.7 mm^2.

Some specimens were saturated with water by evacuation for 1.0 h followed by the introduction of excess of water and the application of a pressure of 0.5 MPa by an inert gas for 24 h.

Compression procedure

The compression experiments were performed with a servohydraulic testing machine manufactured by MTS Systems Corporation supplied with compression plates, a load measuring cell, a piston displacement transducer, an inductive displacement transducer (extensometer), a tape recorder, an oscilloscope, and electronic control equipment. The displacement (compression) of the middle region of the specimen (a length of about 6 mm) was measured with the extensometer attached to the specimen. The total displacement was obtained from the displacement of the piston displacement transducer, which was connected to the lower movable compression plate. The displacement of the end regions was calculated from these two measurements. The load cell was connected to the upper static compression plate to measure the applied force. Regulating components were used for frequency, displacement, and amplitude variations.

At the start of an experiment, a specimen was placed between the two parallel compression plates, and the extensometer was attached to the middle region of the specimen. The specimen was then subjected to the dynamic treatment indicated in Fig. 2. During the first phase, the compression period, the movable compression plate was displaced at a constant rate (1.0 mm/min in all experiments) with a superimposed sinusoidal movement, which was started when there was no risk of separation between the plates and the specimen. When the desired strain level was reached (usually within 4–10%), the specimen was kept at this strain level. During this stress relaxation period (usually 5 min), the dynamic oscillations (up to 84 Hz) were continued. In the testing program strain level, strain amplitude, frequency and time of relaxation were varied.

Analysis of fiber damage

Stress and strain values were recorded during the experiments and later evaluated by use of a memory oscilloscope. To determine hysteresis loss, the stress-strain loops were transferred from the oscilloscope to paper copies and the areas were then cut out and evaluated by weighing. An average loop area was determined each fifth sec from ten single loops recorded within about 1 sec. From the average loop areas, the total energy absorbed by the wood during the oscillations was determined.

The length of the specimen was measured after conditioning at 23 C and 50% RH for one week, and the permanent strain was calculated from the difference in length before and after the mechanical treatment.

It was clearly observed that most of the damage was concentrated in the end regions. Each specimen was therefore divided into three pieces (Fig. 1) that were carefully marked. All pieces, including those from an unstrained reference specimen, were simultaneously delignified in an autoclave using the acid sulfite process. Cooking conditions were defined by 5.6% total SO_2, 1.1% combined SO_2 using Na_2O as the base, a liquor-to-wood ratio of 4:1, and a cooking time of 2.0 h at 135 C after a temperature increase period of 5.0 h. After being washed in running water for two days, a small section from the central region of each piece (Fig. 1) was removed for microscopic study with the aid of a razor blade. The remainder was defibrated by gentle shaking in a plastic bottle filled with water and a few copper rivets. Viscosities of the delignified material from the end pieces of the specimens (two end pieces together), from the middle piece of the specimens and of the reference specimen, were determined according to SCAN-C 15:62 of the Scandinavian Pulp, Paper and Board Testing Committee.

To quantify damage in different parts of the specimen, the following quantities were introduced. The damage in the whole specimen is given by

$$D_{\text{whole}} = \frac{2\eta_{\text{end}}L_{\text{end}} + \eta_{\text{middle}}L_{\text{middle}}}{\eta_{\text{ref}}(2L_{\text{end}} + L_{\text{middle}})}$$

where D_{whole} denotes the viscosity ratio of the whole specimen, L_{end} is the measured length of the two end pieces divided by 2, η_{end} the viscosity of the two end pieces together, L_{middle} is the measured length of the middle piece, η_{middle} the viscosity of the middle piece, and η_{ref} the viscosity of the reference specimen.

The viscosity ratio of the middle piece is given by

$$D_{\text{middle}} = \frac{\eta_{\text{middle}}}{\eta_{\text{ref}}}$$

To calculate the degree of damage in the end region, a correction must be introduced to take into account the fact that the end pieces vary in size and that

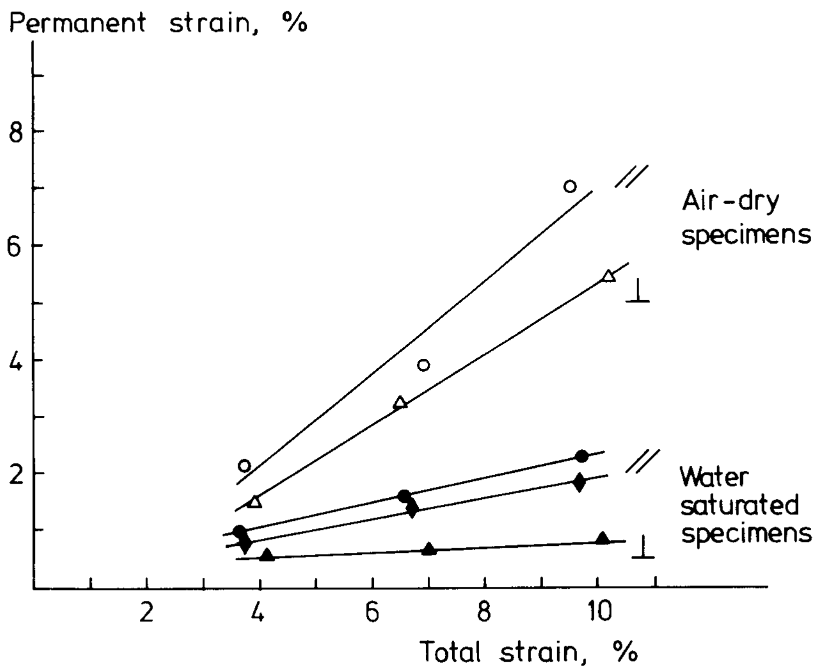

FIG. 3. Permanent strain versus total compression strain. Strain amplitude: 0.27%. Time of relaxation: 5 min.

Symbol	Direction of load	State of wood	Frequency (Hz)
○	Parallel to grain	Air-dry	58
●	Parallel to grain	Water-sat.	58
◆	Parallel to grain	Water-sat.	9
△	Perpendicular to grain	Air-dry	58
▲	Perpendicular to grain	Water-sat.	58

the degree of damage varies along the specimens. The degree of damage in the end regions is thus given by

$$D_{\text{end}} = \frac{\eta_{\text{end}} L_{\text{end}} - \eta_{\text{middle}}(L_{\text{end}} - L_{\text{end}}^{\text{av}})}{\eta_{\text{ref}} L_{\text{end}}^{\text{av}}}$$

where D_{end} is the viscosity ratio of the end region and $L_{\text{end}}^{\text{av}}$ is the average length of all end pieces.

In the figures, each point is the result from one measurement only, i.e., from one specimen.

RESULTS

Effect of total compression strain

Experiments were conducted with the compression force applied parallel to and perpendicular to the grain of air-dry and water-saturated specimens. Compression strains high enough to cause permanent structural deformations were chosen. The permanent strain is shown as a function of total strain in Fig. 3. At a given total strain, the permanent strain is lower in compression perpendicular to than parallel to the grain and is considerably lower in water-saturated than in air-dry specimens.

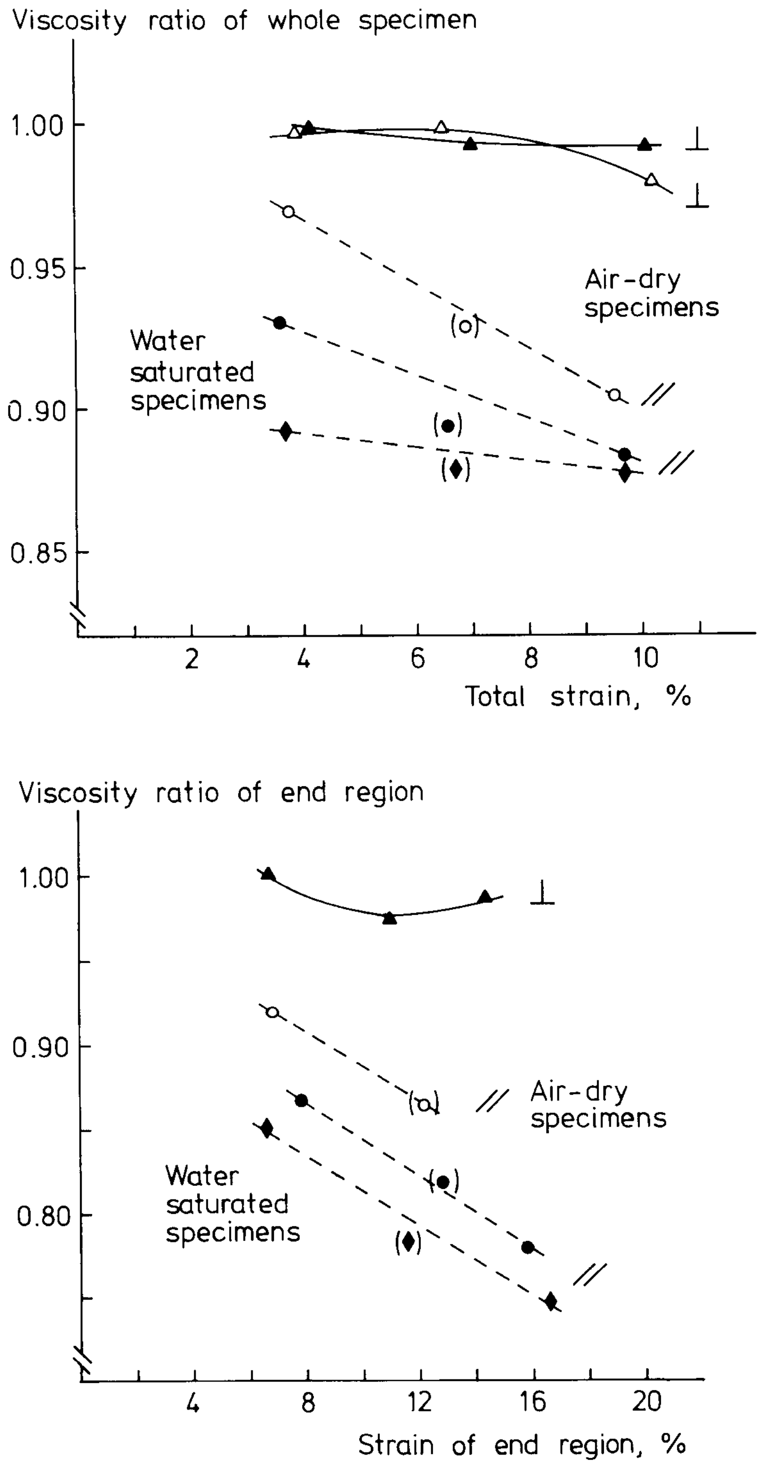

FIG. 4. a. Viscosity ratio of whole specimen versus total compression strain. Compression conditions according to Fig. 3. b. Viscosity ratio of the end region of the specimen versus compression strain of the end region. Compression conditions according to Fig. 3.

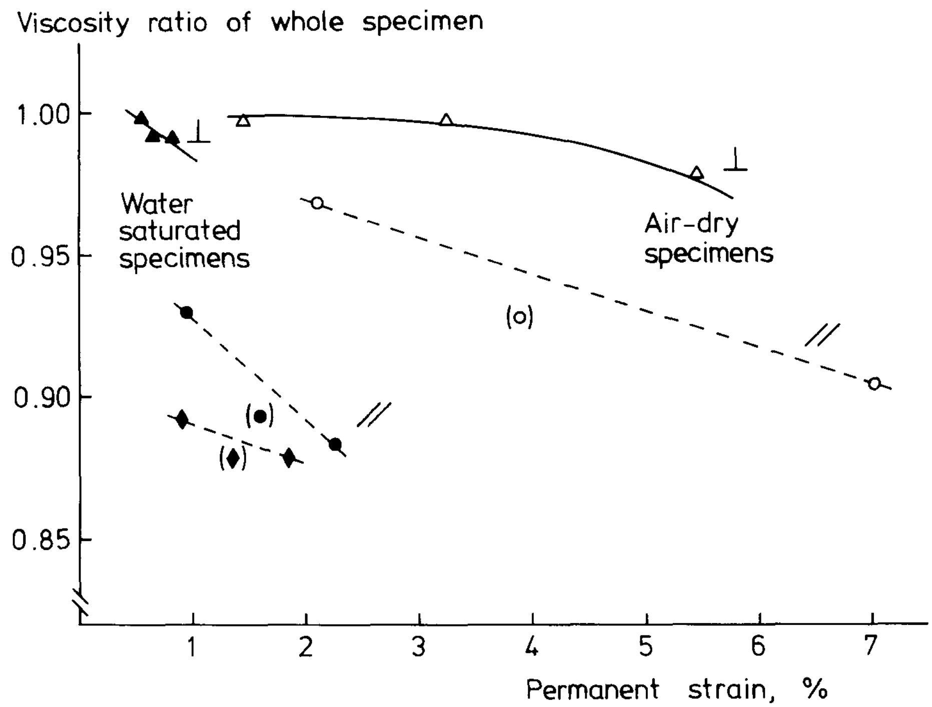

FIG. 5. Viscosity ratio of whole specimen versus permanent strain. Compression conditions according to Fig. 3.

Differences in the structural deformations of the wood constituents under the different conditions contribute to these results. Deformations within both the fiber walls and the middle lamella contribute to the permanent strain. In addition, although the permanent strain is measured in one direction only, there may also be contributions from deformations through sidewise buckling.

In the context of achieving fiber separation with a minimum of fiber damage, permanent deformation in the middle lamella would be an advantage, whereas permanent deformation in the fiber walls would probably be a disadvantage.

The extent of damaging fiber deformation was measured by determining the viscosity after the standardized sulfite delignification of the fibers from the treated wood. The reduction in viscosity ratio (ratio of treated specimen to reference specimen) was, however, different for specimens subjected to the same mechanical treatment but originating from different blocks (Fig. 1). The extent of damage could therefore only be compared using specimens originating from the same block.

The viscosity ratio is presented as a function of total strain in Fig. 4a. As expected, the viscosity decreases, i.e., the extent of damage increases, with increasing compressive strain. In compression parallel to the grain, the viscosity ratio is higher in the air-dry state than in the water-saturated state. In compression perpendicular to the grain, the reduction in viscosity is hardly noticeable. There is here no distinct difference between dry and wet specimens, and the fact that the viscosity ratio is close to unity indicates that only minor damage of the fibers

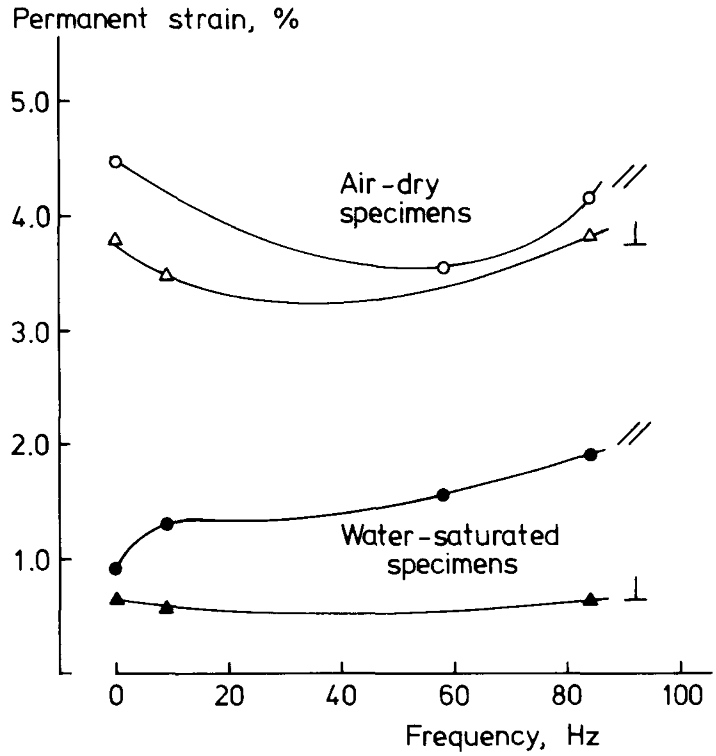

FIG. 6. Permanent strain after a compression straining of 6.5% versus frequency. Strain amplitude: 0.25%. Time of relaxation: 5 min.

Symbol	Direction of load	State of wood
○	Parallel to grain	Air-dry
●	Parallel to grain	Water-sat.
△	Perpendicular to grain	Air-dry
▲	Perpendicular to grain	Water-sat.

has occurred. At 10% total strain, the reduction in viscosity is only 1–2%. The symbols in parentheses represent specimens from other blocks. In this case, the behavior of all specimens is very similar.

The viscosity of the end region (extending about 3 mm into the specimen (see Fig. 1)) is presented separately in Fig. 4b. The end regions have lower viscosity ratios than the whole specimen. This is mainly an effect of friction between the specimen and the compression plates, which makes the end regions more susceptible to damage. Damage to the surface of the specimen during preparation will also contribute to the lower viscosity ratios. When cutting the end regions after compression treatment, some further damage to both the end pieces and the middle piece is introduced. When reference specimens were examined microscopically, a damaged structure was observed over a region extending at most up to about 0.1 mm into the specimen. In accordance with a more damaged end region, most of the obtained strain is also found in this region. This may easily be demonstrated from the strains of the end region and of the middle region, respectively, as was made possible from the displacement measurements of the compression plates (total strain) and from the extensometer attached to the middle of the specimen (middle strain). As one example in compression parallel to the grain of a water-saturated specimen, a total straining of 9.7% yielded a straining of 15.8% of the end region but only a straining of 3.6% of the middle region.

By combining the results in Figs. 3 and 4a, it is possible to compare the context of fiber damage and the permanent strain, as shown in Fig. 5. The most favorable result, high viscosity and high permanent strain, is obtained for air-dry wood in compression perpendicular to the grain. The reduction in viscosity is only 2% at 10% total strain, although the permanent strain exceeds 5%. The permanent strain in this case is thus the result of structural rearrangements, such as deformation in the middle lamella or transverse displacements due to bending, rather than to fiber damage.

The more favorable deformation in the air-dry state than in the wet state in compression parallel to the grain was confirmed microscopically and is in agreement with observations in static compression tests (Dinwoodie 1968; Hartler and LéMon 1969; Keith 1971). In air-dry specimens, the ends were heavily damaged (visualized as slip planes), but deeper into the specimen the amount of deformation was much less. Most of the deformation was concentrated to within about 0.5 mm from the end surfaces. Since the end region viscosity was determined over a region extending about 3.0 mm into the specimen (Fig. 1), the higher viscosity in the end region of the air-dry specimen than in the water-saturated specimen is mainly an effect of less damage in the remaining 2.5 mm of the end piece. In water-saturated specimens, the end effect was less marked. In this case, however, fiber deformation was more frequently distributed along the fibers and penetrated deeper into the specimen. During microscopy all specimens were kept immersed in water. The influence of the oscillations on the deformation will be considered later.

The deeper penetration of fiber damage in the water-saturated state is also indicated by a comparison of the viscosities of the middle pieces of the specimens after different treatments. The viscosity ratio in compression parallel to the grain of the middle region of the specimen varied between 0.93 and 0.99 in the water-saturated state but only between 0.96 and 1.00 in the air-dry state. Average viscosity ratios of the middle pieces in the water-saturated and in the air-dry states were 0.967 and 0.980, respectively.

When the compression was perpendicular to the grain, it was impossible to establish any deformation within the specimen by microscopy since deformations were found only occasionally and they might be a result of the preparation. No end effect could be observed, although a greater part of the total strain was found to be located in the end region, which indicates the existence of such an effect. This is also indicated in Fig. 4 if the strain of the whole specimen is compared with the strain of the end region.

Effect of frequency

The effect of frequency (up to 84 Hz) on the permanent strain is shown in Fig. 6. In the air-dry state, it appears that there is a minimum somewhere in the range between 30 and 60 Hz. In the wet state, the permanent strain is almost independent of the frequency when the compression is perpendicular to the grain, but occurs with increasing frequency in compression parallel to the grain.

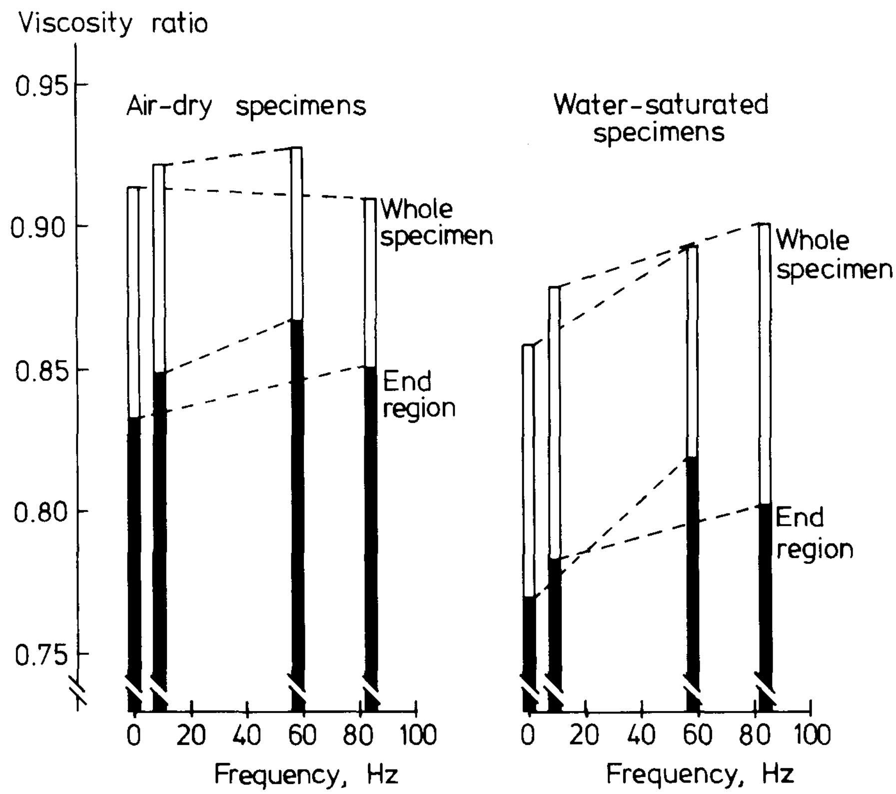

FIG. 7. Viscosity ratio of whole specimen and of the end region at different frequencies. Compression conditions according to Fig. 6. The dotted lines connect specimens from the same block.

There are two important factors that might be responsible for changes in permanent strain when the frequency is varied. First, an increase in the frequency increases the number of cyclic deformations to which the specimen is subjected since the time of treatment was kept constant. Thus, an increase in frequency also increases the possibility of permanent deformations developing. The increase in permanent strain in the higher frequency range might be caused by this effect.

The second factor is related to the viscoelastic behavior of wood. When the frequency increases, the rate of displacement also increases since the strain amplitude was kept constant. This change in rate will influence the behavior of the time-dependent viscous elements in the wood. As viscous behavior is predominantly found in lignin-rich regions (Kollmann 1963), it is very likely that changes in the behavior of such regions may influence permanent strain with changing frequency. In particular, changes in the behavior of the middle lamella, which is rich in lignin, would contribute to changes in permanent strain when the frequency is varied.

A microscopic study of specimens compressed parallel to the grain enabled the deformations within the specimen to be compared at different frequencies. In the end regions the effect of frequency was most marked. At zero frequency the amount of permanent deformation (slip planes) gradually decreased from the surface of the specimen and inwards, whereas at 84 Hz the region close to the surface of the

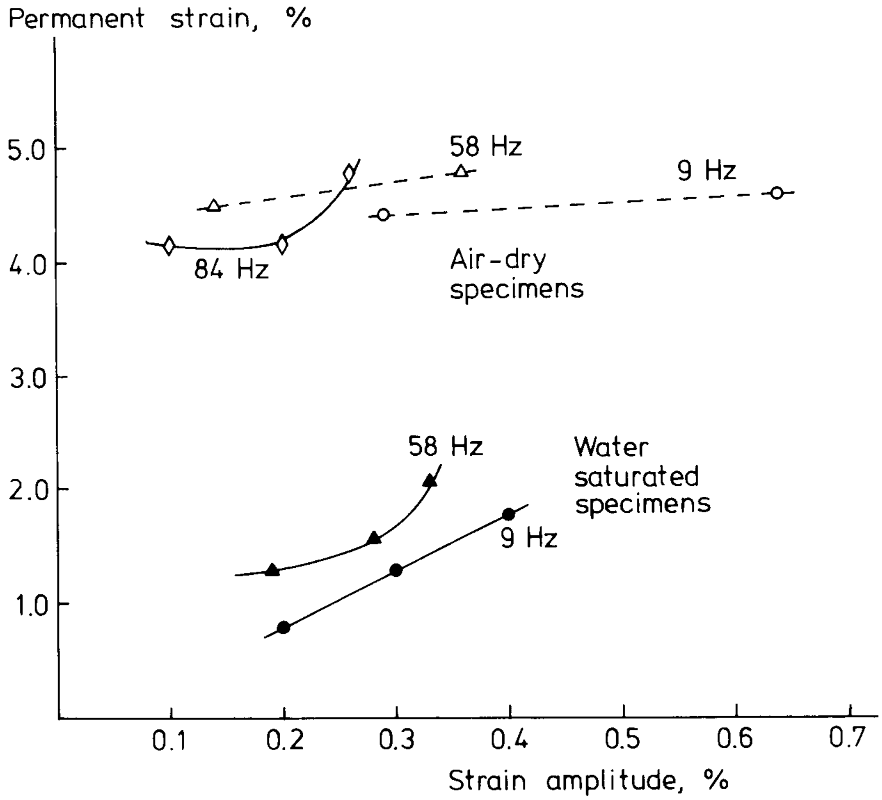

FIG. 8. Permanent strain after a compression straining of 6.5% parallel to the grain versus strain amplitude. Time of relaxation: 5 min.

Symbol	State of wood	Frequency (Hz)
○	Air-dry	9
△	Air-dry	58
◇	Air-dry	84
●	Water-sat.	9
▲	Water-sat.	58

specimen was greatly damaged and the amount of fiber deformation rapidly decreased from this zone and inwards into the specimen. Thus, increasing the frequency decreases the amount of deformation deeper in the specimen. The same effect was observed at constant frequency when the moisture content was decreased, i.e., when the elastic modulus was increased. It thus seems as though the viscous elements of wood respond by increasing the stiffness when the frequency is increased. This is also in accordance with the behavior of most viscoelastic materials (Ferry 1970). In other investigations into the dependence of the elastic modulus of wood on the frequency, diverging results have been reported (Thunell 1941; Kollmann and Krech 1960; Pentoney and Davidson 1962; Goldsmith and Grossman 1967; Sugiyama 1967; Sliker 1973, 1975).

In addition to the change in breakdown observed by microscopy, an increased frequency reduces the total amount of fiber damage measured as reduction in viscosity. This is shown in Fig. 7. Because of differences in response of different

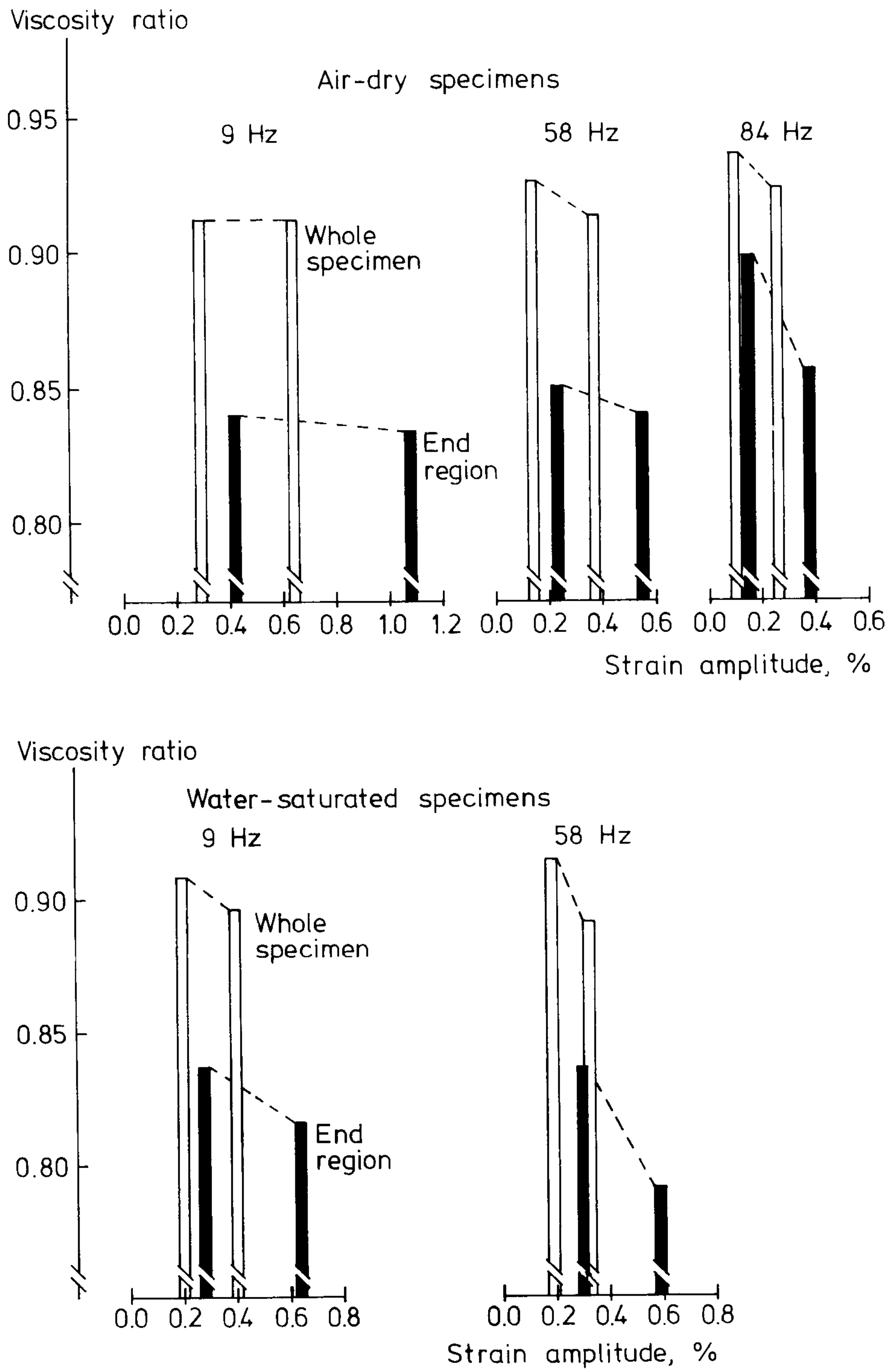

FIG. 9. Viscosity ratios of whole specimen and of the end region at different strain amplitudes. Compression conditions according to Fig. 8. The dotted lines connect specimens from the same block.

blocks, a comparison can be made only between specimens from the same block. The viscosity increases with increasing frequency, particularly in the water-saturated state. As expected, the viscosity of the end region is lower than that of the whole specimen, and the increase in viscosity with increasing frequency is also more evident in the end region. If the permanent strain data from Fig. 6 are taken into consideration, it is found that the most favorable conditions for compression parallel to the grain are provided by a water-saturated specimen at high frequency. Under such conditions, both the permanent strain and the viscosity increase with increasing frequency.

In compression perpendicular to the grain, no fiber damaging effects could be found. The difference in viscosity between compressed specimen and reference specimen was less than 1.5% which is less than the probable experimental error.

Effect of strain amplitude

The effects of strain amplitude during oscillation on the permanent strain and on the viscosity are presented in Figs. 8 and 9 respectively. Only compression parallel to the grain is considered. With increasing strain amplitude, both permanent strain (Fig. 8) and amount of fiber damage (Fig. 9) increase. This is also expected, since an increase in amplitude is equivalent to an increased strain and hence the possibility of introducing permanent deformations increases.

The figures also show that the effect of increasing the strain amplitude increases with increasing frequency. At 58 Hz in the water-saturated state or at 84 Hz in the air-dry state, both permanent strain and viscosity change sharply after a certain amplitude has been exceeded. Thus, high amplitude seems to cause more damage at high frequencies than at low frequencies.

Effects of time of stress relaxation

In this work, the term relaxation time is used to denote the period of time for which a constant average strain level is maintained. This period is not, however, a true relaxation period since a small strain oscillation is superimposed. The average stress does, however, decline during this period as in a true stress relaxation period.

The length of the relaxation period was varied between 0 and 1 h in the parallel to grain experiments and between 0 and 20 min in the perpendicular to grain experiments. The frequency of oscillation was kept at 58 Hz. The effect of the relaxation period on the permanent strain is shown in Fig. 10. The permanent strain increases with increasing time of relaxation, but the greatest effect is evident during the early stage of the relaxation period and the permanent strain seems to attain a constant value at longer relaxation times. The increase in permanent strain with increasing time of relaxation is highest when the compression occurs parallel to the grain in water-saturated specimens. The average stress changes according to the same pattern during the same period, decreasing most rapidly in the early stage of the period.

The viscosity ratios for compression parallel to the grain are presented in Fig. 11. As expected, the viscosity decreases with increasing time of relaxation, the decrease being somewhat more pronounced during the early stage of the relaxation period. The decrease in viscosity with relaxation time is greater in water-saturated

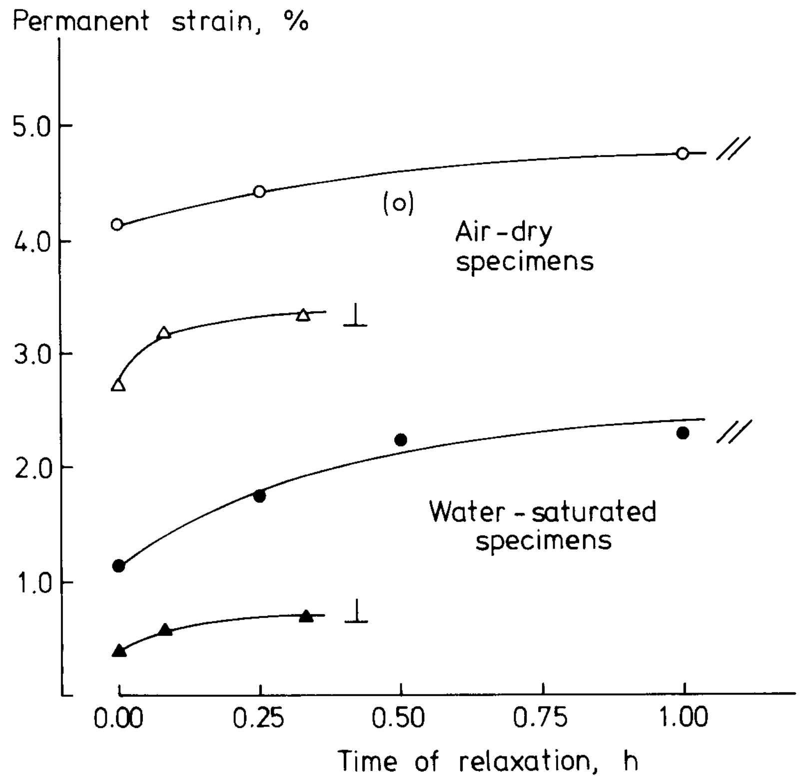

FIG. 10. Permanent strain after a compression straining of 6.5% versus time of relaxation. Strain amplitude: 0.25%. Frequency: 58 Hz. Symbols according to Fig. 6.

specimens. In the perpendicular case there was no reduction in viscosity, which is similar to the negligible effect of frequency on the damage in this case.

Thus, increasing the time of treatment (relaxation) during compression parallel to the grain will have a more marked effect in the wet than in the air-dry state.

Energy consumption

The emphasis in this study has been on the fiber damaging effects of different compression conditions. However, the energy consumption during the deformation of wood is also of considerable importance. Energy will be converted into heat and into mechanical work in the breakdown of the wood structure. The most favorable situation is that in which a high deformation with little fiber damage is achieved with a minimum consumption of energy.

In the experiments, energy has been absorbed both in the overall straining given by the total compression strain and in the straining effect of the superimposed oscillations. The amount of energy absorbed in the first case is related to the stress-compression strain properties of the wood. Table 1 presents some energy absorption values up to a total compression strain of 6.5%. The energy absorbed in the wet state is considerably lower than in the air-dry state, and the energy absorption in compression perpendicular to the grain is considerably lower than in compression parallel to the grain.

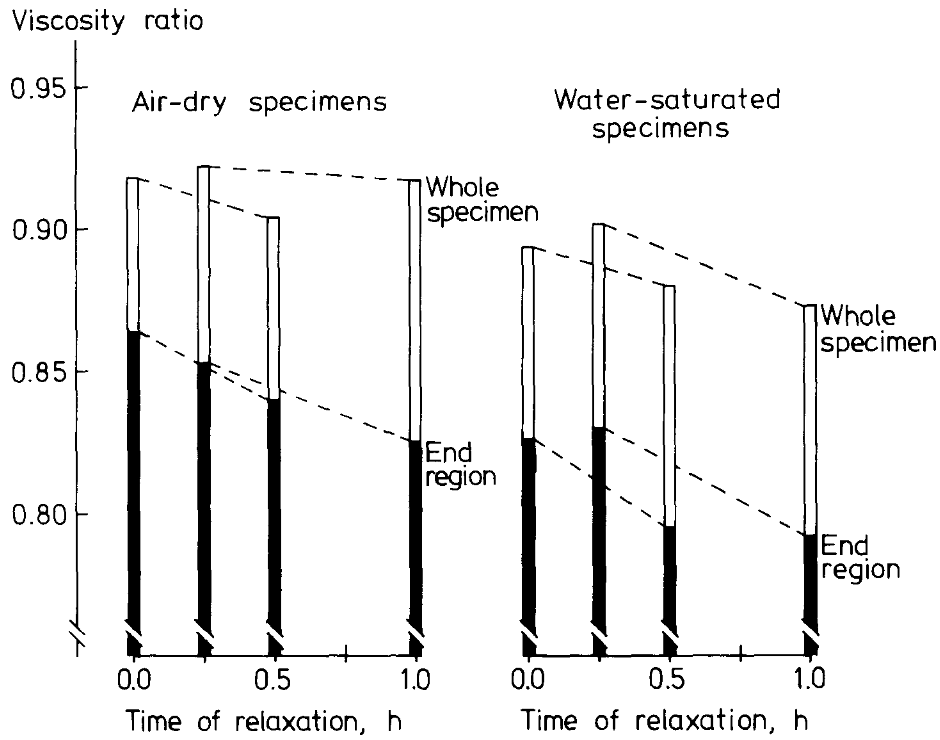

FIG. 11. Viscosity ratio of whole specimen and of the end region at different times of relaxation. Compression conditions according to Fig. 10. The dotted lines connect specimens from the same block.

Thus, considering structural deformation in relation to energy consumption, compression perpendicular to the grain of air-dry specimens is favorable. In that case a relatively high permanent deformation is obtained with negligible reduction in viscosity and at relatively low energy consumption.

The energy absorption due to the superimposed oscillations depends on the stress, on the strain amplitude, and on the internal friction of the wood. This energy absorption was determined in the case of compression parallel to the grain of the water-saturated specimens.

The total amount of energy absorbed, due both to the oscillations and to the overall total straining, is presented in Table 2 for different frequencies and different times of stress relaxation. The energy absorption due to the oscillations is considerable. In a single oscillating stress-strain cycle, the energy absorption is small, but over a series of cycles the amount of energy absorbed soon becomes considerable. The effects on permanent strain and viscosity are also included in the table. Neither the effect on permanent strain nor that on viscosity is proportional to the increase in absorbed energy due to the oscillations with increasing frequency or with increasing time of relaxation. Thus, most of the dynamically supplied and absorbed energy does not contribute to breakdown of the wood but is converted into heat. In the cases of compression perpendicular or parallel to the grain of air-dry specimens, a similar picture seems reasonable, as is seen from the effect on permanent strain and viscosity in Table 1.

TABLE 1. *Energy absorption due to the overall straining, permanent strain, and reduction in viscosity ratio after a compression straining of 6.5% under various conditions. Times of relaxation = 5 min and strain amplitude in oscillating experiments = 0.25%.*

Direction of load	State of wood	Frequency Hz	Energy absorption J/g	Permanent strain %	Reduction in viscosity ratio %
Parallel	Air-dry	0	7.20	4.5	9
		84	7.45	4.2	9
Parallel	Water-sat.	0	2.80	0.9	14
		58	3.00	1.6	11
Perpendicular	Air-dry	0	0.68	3.8	<1
		9	0.87	3.5	<1
		84	0.88	3.8	<1
Perpendicular	Water-sat.	0	0.29	0.66	<1
		9	0.32	0.57	<1
		84	0.32	0.66	<1

The results indicate that the deformation of wood is mainly an effect of the first compression straining cycle and that repeated compression straining has a negligible effect, i.e., compared with the effect of the total compression strain, the effect of the oscillating strain is negligible. It is therefore suggested that the energy absorbed during the initial compression straining of wood from one level of strain to another is the main cause of the structural deformation of wood. Thus, the energy absorbed during the overall compression straining is the main cause for the deformation of wood observed in this study.

In this study, relatively low strain amplitudes were used. By changing the amplitude it would be possible to change the proportion of the energy converted into heat and the energy used in the deformation of wood. At a small amplitude all energy will be converted into heat, but at higher amplitudes more energy will contribute to the deformation of the wood. From an energy utilization point of view, a single straining with sufficiently high amplitude to cause breakdown would give the most favorable breakdown effect. A similar effect, i.e., a decreasing efficiency during prolonged oscillation with respect to both structural deformation

TABLE 2. *Energy absorption, permanent strain, and reduction in viscosity ratio after a 6.5% compression straining of water-saturated specimens parallel to the grain. Strain amplitude in oscillating experiments = 0.25%.*

Frequency Hz	Time of relaxation min	Energy absorption due to: Oscillations J/g	Energy absorption due to: Total strain J/g	Permanent strain %	Reduction in viscosity ratio %
0	5	–	2.8	0.90	14.1
58	5	400	3.0	1.57	10.7
9	5	80	2.7	1.30	12.1
84	5	420	2.8	1.83	9.9
58	0	63	2.5	1.08	10.7
58	30	1,810	2.7	2.21	12.0
58	15	910	2.5	1.76	9.9
58	0.60	3,500	2.7	2.35	12.7

(measured as the change in elastic modulus) and energy consumption, has in compression perpendicular to the grain also been obtained by Salmén (1982).

CONCLUSIONS

Compression perpendicular to the grain of air-dry or of water-saturated specimens results in less fiber damage, measured as a drop in viscosity in relation to the reference after a standardized sulfite delignification, than compression parallel to the grain. At 10% total strain, the reduction in viscosity in compression perpendicular to the grain is only 1–2%, whereas in compression parallel to the grain the reduction is about 10–12%.

Whether the compression is applied parallel or perpendicular to the grain, the deformation of wood measured as permanent strain in the direction of the load is considerably higher in air-dry than in the water-saturated specimens. Thus compression perpendicular to the grain of air-dry specimens is the most favorable situation from the point of view of achieving a structural deformation with a minimum of fiber damage. Compression perpendicular to the grain is also favorable from the viewpoint of energy consumption, since the energy absorption due to the overall total straining is in this case lower than in compression parallel to the grain.

In compression perpendicular to the grain, no extra fiber damage was observed as a result of superimposed small strain oscillations. In compression parallel to the grain, the deformation of wood was affected both by the frequency and by the amplitude of the oscillations. With increasing frequency the extent of fiber damage (reduction in viscosity) decreased. An increase in frequency was most favorable in compression parallel to the grain of the water-saturated specimens. Here, both the deformation in the direction of the load (permanent strain) and the viscosity increase with increasing frequency. At the highest frequency studied (84 Hz), however, the viscosity level is still low compared with the other cases.

The lower degree of fiber damage at higher frequencies is related to less fiber damage deeper into the specimen. At high frequency, most of the fiber damage is concentrated at the ends of the specimen. With decreasing frequency, the damage is distributed more uniformly along the fibers and penetrates deeper into the specimen.

The energy absorbed due to the strain oscillations was determined in compression parallel to the grain of water-saturated specimens. Compared with the energy absorbed due to the overall total straining, much more energy was absorbed during a complete experiment, although the energy absorption in each stress-strain cycle is very small. The magnitude of the total energy absorbed due to the oscillations is not, however, in proportion to the small deformation effects measured. Most of this energy has instead been converted into heat.

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