High Strain Rate Compression and Sliding Friction of Wood under Refining Conditions

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ABSTRACT

Compression and friction characteristics are needed in order to gain a better grasp of the forces acting during refining. To this end, both stress-strain relations and frictional behavior of wood were investigated under simulated chip refining conditions (hot saturated steam, high strain rate compression, and high sliding speed). Two new, custom-designed, experimental set-ups were used. The equipment used for compression tests was based on the split Hopkinson pressure bar (SHPB) technique and the friction tester is a pin-on-disc type of tester. Both pieces of equipment allow a testing environment of hot saturated steam. The wood-steel friction investigations indicate that when making measurements in the lower temperature region (100°C–130°C), surface properties such as lubrication have a great influence on the coefficients of friction. Traces of lubricating layers, comprising fatty acids, were found on friction-tested pine surfaces using a staining technique and light microscopy; in the higher-temperature region no traces of lubrication could be detected in this way. During the friction measurements, the specimens of the different wood species started to lose fibers (produce wear debris) at different characteristic temperatures, indicated by peaks in the coefficient of friction, approximately at 150°C for both Radiata pine and Scots pine while at 165°C for Norway spruce. Since this paper presents the results of initial trials using the SHPB equipment for testing in a steam atmosphere, the most important result is that the measurements made seem consistent with those made in earlier investigations at lower strain rates, which confirms the performance of the equipment. As well, combining the results of the experiments and comparing them with those of refining trials raises interesting possibilities. For example, the generally lower shives content of pine thermomechanical pulps (TMP) than of spruce TMP may partly be explained by differences in the frictional properties of the two kinds of wood.

INTRODUCTION

When wood chips are transformed into single fibers and fiber fragments in the inlets of commercial refiners producing thermomechanical pulp (TMP), the compression strain rates experienced by the fiber material are generally very high and the temperature is approximately 130°C–150°C in the saturated steam environment [1]. The fibers or fiber bundles also rub against the segment material, and against each other, in the narrow gap between the refiner plates, this at even higher temperatures [2-4]. These processes may to a large extent be described as friction processes (surface shearing). Consequently, both compression and friction characteristics of wood under refining conditions are needed to gain a better understanding regarding the influence of the forces acting during refining. To this end, two purpose-designed experimental set-ups were used to investigate wood compression and wood friction under conditions simulating those prevalent in a refiner producing mechanical pulp.

In studying mechanical pulping, impact rate and impact frequency have been both discussed and used [5-11] as influential variables that affect both the energy consumption and the pulp quality obtained. In the present study, the compressive behavior of wood was investigated using a modified split Hopkinson pressure bar (SHPB) set-up. To the best of our knowledge, wood compression tests at high strain rates in a steam environment have not previously been described in the literature. Together with the results of upcoming, more extensive studies, the initial results presented here, obtained using the SHPB equipment, will contribute to increased knowledge in the area. The results should also shed light on some of the basic conditions of which we still lack knowledge; such knowledge is needed to optimize the refining process.

Calculations based on fracture mechanical data indicate that only part of the actual energy consumed during refining is used to create desirable fracture surfaces [12, 13]. Much of the supplied energy is thus consumed in hysteresis losses and processes that mainly develop the fiber properties further, for example, by internal delamination, external fibrillation, and fines generation; friction forces are probably the most important agents in these processes. Friction
between wood and steel surfaces was therefore investigated using a laboratory-scale friction tester, the TT2000, which has previously been described [14, 15].

The study focuses on the Scandinavian wood species, Norway spruce, Scots pine, and birch (*Picea abies*, *Pinus sylvestris*, and *Betula verrucosa*), but some friction measurements of Radiata pine were also included. The frictional properties of birch have previously been found to differ markedly from those of softwood [16].

**BACKGROUND**

Experiments aimed at quantifying the compressive behavior of wood under refining conditions have been carried out, for example, by Björkqvist et al. [17], Uhmeier and Salmén [18], and Renaud et al. [19, 20]. Uhmeier and Salmén used a servohydraulic testing equipment and reached a strain rate of 25/s at 98°C, while Renaud et al. used the split Hopkinson pressure bar (SHPB) technique to test dry wood at high strain rates at room temperature.

The SHPB technique was brought to maturity by Kolsky [21] and is now commonly used to determine stress–strain relationships for materials at high strain rates. A first version of the SHPB equipment, situated at Mid Sweden University, was built by Widehammar [22], who also further developed the testing technique so it would be suitable for wood testing. The results of measurements of spruce wood of various moisture contents at room temperature were published in 2004 [23]. The experimental set-up has now been modified to deal with refining conditions, i.e., compression testing performed in a saturated steam environment (100°C–180°C). So far, initial studies have been carried out in saturated steam environments of approximately 110°C and 143°C.

Most studies of the friction between steel and wood surfaces were performed in the 1950s and 1960s, primarily by Bowden, Tabor, and Atack [24-26]. In their investigations, May and Atack were able to explain fundamental mechanisms of the grinding process (groundwood pulping) [27, 28]. Since the 1950s and 1960s, however, publications in the area have been lacking. Development of the TT2000 friction tester began at Mid Sweden University in 2000, since there were no existing methods or equipment for measuring friction in a saturated steam environment and at high sliding speeds. The friction tester and some softwood frictional data have previously been described [14, 29].

**MATERIALS AND METHODS**

**The High Strain Rate Compression Tester**

The principle of the split Hopkinson pressure bar arrangement is presented in Figure 1. When performing a compression test, the projectile is accelerated to impact velocity by a high-pressure air gun. The loading pulse (the incident pulse) is caused by the axial impact of the projectile into the sender bar. After the impact, a compressive wave propagates from the impacted ends into each bar. When this compressive wave reaches the specimen, the sender bar compresses the specimen. A portion of the pulse is then reflected from the interface, while the remainder is transmitted through the specimen to the receiver bar.

![Figure 1. Set-up of SHPB experiments.](image)

The force and relative displacement of the ends of the specimen are measured from the continuous strain–time histories in the sender and receiver bars. These strain pulses are recorded by resistance strain gauges mounted on the surfaces of the sender and receiver bars (locations indicated in Figure 2 by $\varepsilon_l$, $\varepsilon_r$, and $\varepsilon_t$). A general description of the evaluation procedure is given in Gray [30] and Gray and Blumenthal [31].
The SHPB experimental set-up was modified by encapsulating the sender and emitter bars together with the specimen in a pressure vessel, so that everything inside the pressure vessel had the same temperature. The equipment is designed to handle testing in temperatures up to approximately 180°C and strain rates of 1000/s. The strain rates achieved in this preliminary study ranged from approximately 200/s to 620/s and the temperatures chosen for the tests were approximately 110°C and 143°C.

![Image](image1.png)

**Figure 2.** The modified split Hopkinson set-up.

The bars are made of an aluminum alloy (EN AW 2024-T3511) and have a quadratic cross-section of 12×12 mm. The yield strength of the 2024 alloy is temperature dependent, being approximately 435 MPa at 20°C and 350 MPa at 180°C (approaching 280 MPa after 1000 h of exposure). The faces of all bars were ground flat and parallel.

### The Friction Tester

The TT2000 friction tester depicted in Figure 3 was used to register friction forces between wood specimens and a smooth steel surface. The following testing conditions can be adjusted: sliding speed (0.5–100 m/s), temperature/pressure (saturated steam pressurized to various degrees), normal load (1–20 N), and counter surface (can be changed).

![Image](image2.png)

**Figure 3.** The TT2000 friction tester [15].

When making a measurement, the steel disc was rotating at 2000 r.p.m., the lid was closed, and the saturated steam environment in the friction tester was set to a chosen temperature/pressure (testing interval: 100°C–170°C). A normal load was then applied from the outside by means of a loading device connected to a loading arm inside the pressure vessel. The normal load used here was 14 N, which corresponds to a stress of approximately 100 kPa in compression. The relative sliding speed between the test surfaces was 25 m/s, which is higher than in most friction measurements.

![Image](image3.png)

**Figure 4.** Sketch of a typical specimen used for both compressive tests and friction measurements.
All friction measurements were performed on the surfaces of tangential sections of earlywood, sliding against the steel disc in a direction parallel to the fibers of the specimens. Both the equipment and the measurement technique have been previously described in greater detail [14, 15].

Raw Material and Specimen Preparation

The raw materials used in this study were sapwood sections from green logs of Norway spruce (Sweden), Scots Pine (Norway), and birch (Sweden). In addition, sapwood from Radiata pine (Tasmania, Australia) was used in the friction studies. Selected sections of wood were cut from the bottom log 1.5–2 meters above ground level. Data describing the wood used for the specimens are presented in Table I.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Moisture content (%)</th>
<th>Extractives content (% DCM)</th>
<th>Distance between annual rings (mm)</th>
<th>Surface roughness (µm) of friction test surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce (Picea abies) sapwood</td>
<td>0.37 (±0.02)</td>
<td></td>
<td>1.5 (±0.2)</td>
<td>3.8 (±0.4)</td>
<td>6.8 (±0.2)</td>
</tr>
<tr>
<td>Pine (Pinus sylvestris) sapwood</td>
<td>P. sylvestris: 0.46 (±0.02)</td>
<td>P. radiata: 0.45 (±0.02)</td>
<td>2.8 (±0.1)</td>
<td>4.3 (±0.4)</td>
<td>7.0 (±0.2)</td>
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<tr>
<td>Birch (Betula verrucosa) sapwood</td>
<td>0.61 (±0.02)</td>
<td></td>
<td>2.1 (±0.2)</td>
<td>3.5 (±0.3)</td>
<td>8.5 (±0.3)</td>
</tr>
</tbody>
</table>

The wood specimens used for the friction measurements were 12×12×12-mm cubes. The compression tests were performed on both 12×12×12-mm and 6×12×12-mm specimens. The specimens were prepared by cutting thin sections of wood away from the surfaces with a sledge microtome. This technique resulted in smooth surfaces, which also allowed high accuracy in the specimen’s dimensions. The compression tests were performed in the axial direction of the specimens (parallel to the fiber direction). The friction tests were performed on tangential, earlywood surfaces of specimens where the annual rings were as parallel to the surface as possible (see Figure 4).

Surface roughness, $R_a$, based on height profiles was determined by optical high-resolution scanning of random specimens. The equipment used for this was the MicroProf® profilometer (Fries Research and Technology GmbH, Bergisch Gladbach, Germany). Density was experimentally estimated by dividing the dry weight for each of 6 specimens by its volume. Similarly, the moisture content was determined as the weight of water in each of 6 specimens divided by its total wet weight.

To detect the presence of extractives, a stain selective for fatty acids only, Sudan Orange (Sigma-Aldrich), was used in combination with light microscopy.

RESULTS AND DISCUSSION

Results of the Friction Measurements

Friction measurements were made between wood specimen surfaces and a counter surface of stainless steel. The temperature in the contact zone between the specimen and the steel surface was very close to the surrounding steam...
temperature. By drilling very small holes through the specimens, a thin thermo-couple could be placed very close to the wood-steel interface. None of the registrations by the thermo-couple showed a higher temperature rise than 3°C. A friction measurement is normally completed in 6 seconds but even when extending that time (of curiosity) up to minutes the temperature in the interface was not significantly higher. The highest measured temperature rise in the contact zone was 4°C, which was after two minutes of sliding contact (normal load 14 N).

In Figure 5 the frictional properties of birch, Scots pine, Radiata pine, and Norway spruce are presented as functions of the surrounding steam temperature. At temperatures ranging from 100°C to approximately 130°C, the friction coefficient between birch and steel was quite high. The softwood species had significantly lower coefficients of friction, Scots pine having the lowest measured friction, followed by Norway spruce and Radiata pine. This sequence is in accordance with the extractives content (%DCM) of the various species: low friction was associated with high extractives content, and higher friction with lower extractives content (cf. Figure 5 and Table I). In this temperature range, surface properties seem to determine the friction level, for example, the friction between Scots pine and the steel surface was assumed to be reduced by the presence of a lubricating film or layer. To support this assumption, thin sections of the pine surfaces that had been friction tested at various temperatures were stained with Sudan Orange, which is soluble only in fatty acids (a major component of wood extractives). Small drops of fatty acids were revealed all over the surface that had been friction tested at 110°C, indicating that a lubricating layer or film was formed at the wood-steel interface during friction testing (see Figure 7). The presence of fatty acids is probably an indication of other component groups of extractives as well. When using this staining technique on specimen sections tested at temperatures above 130°C, there were no signs of a lubricating film or layer; instead, the fatty acids observed were found more in their natural locations in the wood (see Figure 8).

The birch surfaces tested at 110°C also had some fatty acids present at the surface, but they did not seem to have spread over the same extent as on the pine surfaces. Spruce and pine wood contain resin channels oriented both vertically and radially in the wood matrix, and some of these resin channels will be directed vertically against the steel disc during the friction measurements. Birch wood does not contain these resin channels; instead, the extractives are contained and transported in rays comprising parenchyma cells, making the extractives less physically accessible. Thus during the friction measurements, layers or films of wood extractives at the interface are likely to be formed more easily with pine and spruce than with birch specimens. As well, the smoother test surfaces of pine and spruce (see surface roughness parameters in Table I and the images in Appendix A) could also have made it easier to establish and sustain an effective lubricating regime between the specimens and the disc. The rougher test surfaces of birch were probably more difficult to lubricate with the available amount of extractives.

Figure 5. The coefficient of friction for birch, pine, and spruce specimens as a function of the surrounding steam temperature. The counter surface was of smooth steel.

Figure 6. The 95% confidence intervals for the birch and Scots pine specimens are indicated here as shaded areas. Confidence intervals corresponding to the spruce and Radiata pine curves in Figure 5 are presented in Svensson et al. [15].
Fatty acids

Figure 7. Thin section of a Scots pine test surface friction tested at 110°C. The section was stained with Sudan orange, soluble in the fatty acids found among the wood extractives.

Figure 8. Section of a Scots pine test surface friction tested at 163°C.

During the friction measurements, the specimens of the different wood species started to lose fibers (produce wear debris) at different characteristic temperatures (“wear-off temperatures”), indicated by a peak in the coefficient of friction. The pine species (*Pinus sylvestris* and *Pinus radiata*) began to produce wear debris at approximately 150°C, while spruce held on to its fibers up to somewhere between 160°C and 165°C (see Figure 5). Birch, on the other hand, did not produce any wear debris in the temperature interval investigated. However, in a separate study of birch–steel friction, wear was registered for birch, after impregnating the specimens with sodium sulfite and alkali [16]. For spruce, measurements indicate that the wear-off temperature can be shifted lower by using sodium sulfite of various concentrations [15].

At temperatures above approximately 130°C, the frictional behavior was unlikely determined by the presence of lubricating extractives in the wood–steel interface, but was assumed to be more related to the bulk material properties. Certainly, as long as extractive substances were present in the contact zone between the specimen and the disc they probably somewhat affected the friction. However, assuming that the contact surfaces at higher temperatures were not efficiently lubricated by the extractives, what properties could possibly explain the frictional differences between the species? There are many possible variables that together could influence the frictional properties; two of the most obvious variables are discussed below: material stiffness and the size of the real contact area in each measurement.

The stereomicroscope images in Appendix A illustrate how at higher temperatures the test surfaces become more or less deformed. The specimens with the most deformed surfaces, tested at each temperature, were chosen for the images. With both the spruce and pine surfaces, whole fiber bundles were “combed” out from the surfaces at higher testing temperatures. These fiber bundles protruded from the surfaces, making them rough and thus decreasing the real contact areas that were possible to establish during the friction measurements. “Real contact area” refers to the area actually in contact with the steel surface, not the *nominal* contact area of 12×12 mm. The real contact area is always smaller than the nominal area due to surface roughness. The higher surface roughness here probably resulted in higher “point loads” on the individual contacts, which could explain why the fibers were eventually worn off the surfaces (at or above the wear-off temperature). The birch specimens also became deformed but not to the same extent as the softwood specimens. Smaller fiber bundles were combed out from the birch surfaces than from the pine and spruce surfaces. When comparing the images in Appendix A, of the three wood species at the two highest temperatures, it could be that when the specimens were pressed against the steel surface, birch had the largest contact area. This was due to the “valleys and grooves” in the softwood surfaces causing higher surface roughness and smaller real contact areas. With the larger contact areas of the birch specimens, the normal load applied during testing was spread out more, giving lower point loads (larger stress distributions).
The differences in contact area when comparing tests performed at high temperatures (see surfaces in Appendix A) could perhaps explain why the surfaces started to lose fibers at different characteristic wear-off temperatures. However, these differences did not seem to determine the magnitude of the friction force, since there were specimens with no visible deformations at each tested temperature the corresponding friction coefficients of which were still clearly within the data scatter (see confidence intervals in Figure 6). The energy needed to cause the surface deformations was entirely caused by the friction forces arising between the surfaces (surface shearing), so it would seem natural that with a higher friction force (coefficient of friction) the surface would become more deformed. The specimens with small or no visible deformations when tested at high temperatures were exceptions that could instead be explained by higher energy losses in the form of hysteresis losses in the bulk material; that is, if no cracks were initiated in the surface, the friction energy would still be absorbed in some way by the surface. In view of the fact that a visco–elastic material was being investigated, hysteresis losses probably occurred, to a greater or lesser extent, throughout the measurements.

When the wood material is deformed and compressed in a refiner, the material stiffness is essential for the outcome [32-34]. In the friction contacts, the resistance to surface shearing should be higher for a stiffer wood material provided that there is little or no lubrication. At the same time, the absence of lubrication enables energy transfer to the bulk of a visco–elastic material (hysteresis losses), which also contributes to the magnitude of the coefficient of friction. This was reported for rubber surfaces by Grosch in 1962 [35], and further investigated theoretically by Persson in 1998 [36]. Consequently, wood stiffness is probably essential to unlubricated wood friction, though high stiffness does not necessarily mean high friction. Regarding the influence of friction on the course of events in refining, however, additional information about the bulk material’s response to mechanical loading is evidently needed; this matter is discussed further in the following section.

**Results of High Strain Rate Compression Measurements**

The split Hopkinson pressure bar set-up was used to obtain relevant stiffness data regarding the refining process. This was done by firing the projectile towards the sender bar, which rapidly compressed the specimens.

![Figure 9. Negative stress versus negative strain for spruce specimens compressed axially (in the fiber direction) at three different temperatures; 6-mm-long specimens with cross-sections of 12×12 mm were used in the tests.](image)

![Figure 10. Negative stress versus negative strain at 110°C for birch, pine and spruce wood compressed axially (in the fiber direction); 12-mm-long specimens with 12×12 mm cross-sections were used in the tests.](image)

Figure 9 presents the negative stress as a function of the achieved negative strain (compression) for 6-mm-long spruce specimens tested under three different temperature regimes (20°C under ambient conditions, 110°C and 143°C in saturated steam). Representative curves chosen from three measurements on separate specimens, at each temperature, are presented in the figure. The projectile was fired from the air gun at a pressure of 1 MPa, i.e., the...
pulses could be expected to contain an equal amount of energy in each trial. The plateau stress registered for this pulse load was, as expected, highest at room temperature. At 110°C in saturated steam the plateau stress is approximately half of the stress registered at room temperature under ambient conditions; then again, at approximately 143°C in saturated steam the plateau stress is reduced considerably. The strain rates achieved, at the three different temperature regimes chosen for the tests, are approximately 550/s for the 20°C tests and 580-620/s for the tests performed at higher temperatures in steam. The strain rates as well as the strains could, if desired, have been increased by using a higher pressure in the air gun.

Figure 10 presents representative stress–strain curves registered for birch, Scots pine, and Norway spruce specimens in a 110°C steam environment. Because the specimens used in these tests were 12 mm long, the recorded strains are lower than those presented in Figure 9, and the strain rates achieved were approximately 300/s. The figure reveals differences in the plateau stresses for the three wood species, birch wood displaying the highest resistance to compression, followed by pine and spruce.

Young’s modulus (the E-modulus) was not calculated from either of the curves in Figures 9 and 10, since the initial slopes of the curves are very sensitive to small calculation errors in the evaluation procedure. However, the curves in Figure 9 strongly indicate that the material stiffness decreases as the surrounding temperature increases, as expected. In these initial trials using the SHPB equipment, the most important result is that the measurements seem to be consistent with earlier ones made at lower strain rates (e.g., Uhmeier and Salmén [18]), which confirms the performance of the equipment.

Discussion of the Influence of Friction and Compression on the Course of Events in Refining

Figures 11 and 12 are from Norgren et al. [37] and depict the effects of TMP-reject refining at a much higher temperature than that normally used. The full-scale reject refining trial was performed at the Ortviken paper mill in Sundsvall, Sweden. The HT reject (HT in the figures) was preheated at above 170°C while the reference reject (“Reference” in Figures 11 and 12) was preheated at a more normal refining temperature of approximately 130°C. High-temperature preheating has been demonstrated to decrease the energy needed to refine to a certain degree of freeness (see Figure 11).

Friction properties can probably partly explain the reduced amount of energy needed. At 170°C the wood material is very soft and the friction coefficient for native spruce wood is low (cf. Figure 5). A low friction coefficient should be beneficial in terms of keeping the energy consumption low, provided the energy required for mechanical defibration can still be transferred from the refiner plates to the fiber material. In this case, enough energy was transferred to the fibers, since the shives content remained low (see Figure 12) and was even significantly reduced by HT treatment.
While measuring the friction on spruce at 165°C and above, fibers were continuously worn off the wood test surfaces by the action of the friction forces (see Figure 5). This implies that at these temperatures, the wood matrix was unable to hold onto the individual fibers to any great extent, since they were easily removed by quite small friction forces (low friction above 170°C). This phenomenon could explain the reduced amounts of shives found in the HT trials, and is also in line with the results presented in 1980 by Koran; he concluded that 170°C was the optimum temperature, in terms of energy consumption, for separating spruce fibers [13].

In 1992 Richardson et al. found that Radiata pine TMP contain substantially less shives and more long fibers than do spruce pulps produced under the same pulping conditions; the authors suggested that the processing of Radiata pine pulps would benefit from the use of a lower presteaming temperature than normally used for spruce [38].

As in the above discussion of the HT reject, the low shives content of Radiata pine TMP could probably be partly explained by the results of the friction investigation. As mentioned earlier, the characteristic wear-off temperature for the pine species is significantly lower than that for the spruce. It should thus be possible to produce pine pulps at lower temperatures that are reasonably free of shives, especially considering the higher friction coefficients of pine (cf. Figure 5) in the 130°C–160°C interval of interest. Furthermore, during the friction measurements, considerable loose fiber material was noted at and above the characteristic wear-off temperature for Radiata pine. When comparing the mass loss between the species, Radiata wood was most prone to losing fibers, followed by Scots pine and Norway spruce. No mass loss was noted for the birch specimens in the temperature interval investigated and under the normal load used.

CONCLUSIONS

The wood–steel friction investigations demonstrated that:

- during friction measurements in the lower temperature region (100°C–130°C), surface properties such as lubrication have a great influence on the coefficients of friction. Traces of lubricating layers, comprising fatty acids, were found on friction-tested pine surfaces by using a staining technique and light microscopy.

- in the higher-temperature region (130°C-170°C), no traces of lubrication could be detected by using the cited staining/microscopy technique.

- during the friction measurements, the specimens of the different wood species started to lose fibers (produce wear debris) at different characteristic temperatures (“wear-off temperatures”), indicated by a peak in the coefficient of friction, approximately at 150°C for both Radiata pine and Scots pine while at 165°C for Norway spruce.

This paper presents the results of initial trials using the SHPB equipment for testing in a steam atmosphere. The most important finding is that the measurements made seem consistent with earlier ones, made at lower strain rates; this confirms the performance of the equipment.

Predicting or explaining refining trends by looking at laboratory data is no trivial matter. However, by combining the experimental results and comparing them with those of refining trials, interesting observations can be made. For example, the generally lower shives content of pine than of spruce TMP can be partly explained by differences between the frictional properties of the two species. Though refining involves not only compressive and frictional forces, understanding these forces at least represents a step towards greater knowledge in the area.

ACKNOWLEDGEMENTS

The authors are grateful to Staffan Nyström (Mid Sweden University) for his invaluable help with the SHPB strain gauges and data collection, and for generally sharing his technical and electronics expertise with us. Dr. Mats Rundlöf (Capisco Science & Art) is greatly acknowledged for creative discussion of and comments on the manuscript.
REFERENCES


Appendix A. Stereomicroscope images of test surfaces after friction measurements at various temperatures.

<table>
<thead>
<tr>
<th>Pine</th>
<th>Spruce</th>
<th>Birch</th>
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<tr>
<td><em>Pinus radiata</em></td>
<td><em>Picea abies</em></td>
<td><em>Betula verrucosa</em></td>
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<tr>
<td>Prior to test</td>
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<td>119°C</td>
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