THE FIBER-SATURATION POINT OF WOOD
AS OBTAINED FROM
ELECTRICAL CONDUCTIVITY MEASUREMENTS

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In cooperation with the University of Wisconsin
A method for determining the fiber-saturation point of wood by electrical conductivity has been developed so as to minimize the effect of moisture gradients. Small specimens less than a fiber length in thickness were used.

The same linear relationship between the logarithms of electrical conductivity and of moisture content exists at the lower moisture-content values, for all of the species studied. The point of tangency of the line showing this relationship with the curve for higher values of moisture content, which represents the fiber-saturation point, differs slightly among the species, and the upper part of the curve does also.

No perceptible deviation between the results for green redwood and for resoaked redwood was observed.

Removing the extractives of redwood raises its fiber-saturation point.

Fiber-saturation values obtained by other means are given for comparison with those obtained by the electrical conductivity method.

Although it has long been known that variations in moisture content below a certain limit affect many important physical properties of wood, yet the determinations of this limit, called the "fiber-saturation point," have been few in number and questionable in accuracy. When it is considered that the strength of wood is greatly affected by absorbed water and not at all by free water, that the swelling and shrinking of wood are due entirely to absorbed water, and that in drying wood the absorbed water is the more difficult to evaporate, the practical importance of accurate determinations of the limit of absorption — the fiber-saturation point — is at once evident.

The term "fiber-saturation point" was first used in connection with wood to designate the moisture content below which further reduction of

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moisture caused changes in the strength of the wood. The absorption of
water by wood belongs to the same general class of phenomena as the absorp-
tion of various liquids by different fibrous materials and elastic jellies,
and it very closely resembles the absorption of water by other cellulosic
fibers. In these other absorptions the terms "limit of the absorption" of
the liquid by the jelly and the "limit of the solubility" of the liquid in
the jelly are used to express exactly the same conception as "fiber-
saturation point."

Expressed in the terms that pertain specifically to its cellular
structure, the saturation point of a wood fiber may be considered as the
state in which the cavity of the fiber is entirely free from moisture and
its wall is saturated throughout. Shrinkage of a drying fiber begins at
this point, its strength properties begin to change, and its electrical con-
ductivity varies at different rates above and below the point. Accordingly
the fiber-saturation point of a green piece of wood losing moisture may be
defined provisionally as the moisture condition of the piece at which there
is a break in the variation of the rates of change of its physical properties
with change in moisture content of the piece. The fiber-saturation point
may then be obtained by determining the point of break in such rate of change
for any of the physical properties concerned. Non-uniformity in the moisture
condition of a piece of wood of tangible size, which always obtains to some
extent, affects the accuracy of the determination, however, and consequently
different methods of determination have different degrees of accuracy.

The term "fiber-saturation point," as used throughout this discussion,
will accord with the preceding provisional definition.

Relation between Conductivity and Moisture Content

The electrical resistance of wood, as the author2 has already pointed
out, changes at a tremendous rate with changes in moisture content below
the fiber-saturation point. From an oven-dry condition to the fiber-saturation
point, a change in moisture content from zero to about 30 percent of the
weight of the wood, the conductivity increases a million fold. Over this
range of moisture-content values a linear relationship exists between the
logarithm of the electrical resistance, or the logarithm of the electrical
conductivity, and the moisture content.2 This relationship, however, fails
to hold for higher values of moisture content. From the fiber-saturation
point to the complete filling with water of the coarser capillary structure,
which in some cases is more than 200 percent moisture content on the basis
of oven-dry wood, the electrical conductivity changes less than fifty fold.
The diminution of the rate of increase of electrical conductivity with an
increase in the moisture content above the fiber-saturation point provides
a method of determining the moisture content corresponding to this point.

Myer and Rees have used this method of determining the fiber-saturation point of wood. They unfortunately used large specimens of wood, cylinders 2 inches long and 1 inch in diameter, a procedure that not only increases the difficulty involved in experimentation, but tends to decrease the accuracy of the measurements as well because of the unavoidable moisture gradients that result during the drying of the specimens. They also used a somewhat different method of obtaining from their curves the points corresponding to fiber saturation, which will be described later.

**Effect of Uneven Distribution of Moisture**

On account of the parabolic form of the function expressing the relationship between electrical conductivity and moisture content, it is essential that the moisture distribution of the test specimens be uniform for each measurement. If the specimens are conceived to be made up of thin laminations perpendicular to the path of the current, the electrical resistance of a specimen will be the sum of the individual resistances of the respective hypothetical laminations. Then, since the resistance of wood varies in a parabolic manner with change in moisture content, the total resistance will be at a minimum when the moisture distribution is uniform. For example, with a specimen having a 4.5 percent moisture gradient and moisture-content values of 9.5 percent at the center, 5.0 percent at the surface, and an average of 8.1 percent, the experimentally determined value of electrical resistance would be 60 percent above the value correct for a uniform distribution of moisture; this excess in resistance corresponds to a deviation in moisture content of 0.8 percent. Such a deviation increases at a tremendous rate with increase in the slope of the moisture gradient. The nature of the gradient -- that is, whether it is of the drying or the absorbing type -- will also affect the results; an absorbing gradient is likely to cause more inaccuracy than a drying one of similar severity. The figures of this example thus illustrate to some extent the great importance of attaining uniform moisture-content conditions for investigative purposes.

Myer and Rees attempted to attain a uniform moisture distribution by holding the specimens for 2 days in sealed jars after each increment of drying, so that the moisture might be redistributed. Moisture gradients below the fiber-saturation point will gradually disappear as a result of diffusion when the specimens are held under non-drying and non-absorbing conditions. The process of diffusion, however, is extremely slow. Above the fiber-saturation point no such diffusion tendency exists, so that in a large specimen it is practically impossible to attain moisture-content values that are both high and uniform.


5 A more extensive description of the effect of moisture gradients upon the electrical resistance is discussed in another paper by the author to appear later.
Dimensions of Specimens

The simplest way to minimize the difficulties of the electrical conductivity method is to use small specimens. In the research now reported, transverse sections of disk form 1.0 cm. in diameter and 0.2 to 0.35 cm. thick were used. As the thickness of these disks is less than the average fiber length, practically all of the fibers are cut across at least once, thus exposing nearly all of the fiber-cavity capillaries (lumina) to the drying conditions of the surface of the wood. Such exposure not only minimizes the gradients set up in the specimens, but also greatly reduces the time for adjustment of the moisture distribution after a period of drying that has carried the moisture content below the fiber-saturation point.

Apparatus

The apparatus used consisted of a portable suspension galvanometer (Leeds and Northrup No. 2420-C), an Ayrton shunt, a contact clamp for holding the wood sections, a key switch, and a source of direct current consisting of single dry cell of 1.5 volts for the high-moisture-content readings, and a 90-volt battery for the low-moisture-content readings. The shunt was connected across the galvanometer and in series with the source of current, the wood contact clamp, and the key switch.

The resistance of the shunt was varied so as to allow the entire current carried by the test specimen and different fractional parts of it, as desired, to flow successively through the galvanometer; these galvanometer currents had the relative values of 1.0, 0.1, 0.01, and 0.001. The settings of the variable shunt, together with the two different applied potentials, made it possible to cover a range in conductivity of more than 100,000 times.

The clamp for holding the small wood specimens consisted essentially of a rubber-tubing screw clamp (Hofmann type) mounted on a wooden panel. A lead contact disk, 1.0 cm. in diameter and 0.2 cm. in thickness, having an appropriate electrical connection and mounted on mica insulation, was fastened over the bottom arm. The specimen was placed on this contact disk, a similar lead disk was placed on top of the specimen, and the clamp with an electrical connection on its head was then screwed down securely on the pile of lead and wood. When the pressure was sufficient to give a good contact between the disks and the specimen, a negligible deviation in the resulting current was obtained on reclamping.

Though a current flow method rather than a zero flow method was used, the effect of possible polarization was found to be negligible because of the extremely low conductivities measured, maximum values being of the order of the conductivity of distilled water.

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Specimens Studied

The heartwoods of eight different softwoods and one hardwood were studied. All specimens had been previously air-dried, with the exception of the redwood. The specimens were therefore saturated by soaking in distilled water, prior to the measurements, until they sank. They were extracted only in the cases designated, and then with either hot water or alcohol.

Experimental Procedure and Results

In beginning the experimental work, after the adhering water had been shaken from the specimen under investigation, the weight of the specimen in a small sealed weighing bottle was obtained, and its electrical conductivity was determined. It was allowed to dry in the air for 5 to 10 minutes and was then sealed in the weighing bottle for 15 minutes to 18 hours before the next measurement was made. Experiments showed that for these small specimens 2 hours or so was a sufficient time to hold the specimens under non-drying and non-absorbing conditions in order to insure any possible adjustment in the distribution of the moisture taking place.

Figures 1 and 2 show graphically the results for redwood. The percentage moisture-content values calculated on the basis of oven-dry wood are plotted as abscissas, and the logarithms of the specific conductance of the wood are plotted as ordinates. Both curves show a linear relationship between the moisture content and the logarithm of the electrical conductivity below about 30 percent moisture content and above this point an increasing deviation from this relationship with increasing moisture content. All of the species studied gave practically identical lines for the linear-relationship portion. The only real variations between species were slight differences in the location of the point of tangency of the straight line and the curve, and slight differences in the nature of the curve itself.

Figure 1 presents the results for two specimens of green redwood and their corresponding resoaked values after oven-drying. The data indicate slight but consistent differences between two specimens of the same kind of wood, although the differences are practically within the range of experimental error. The data also indicate that complete drying has no perceptible permanent effect upon the moisture content-electrical conductivity relationship.

Fiber-saturation Points Determined by Different Means

The point of tangency of the curved and the straight-line portions of each graph marks the moisture-content limit for which the initial moisture content-electrical conductivity relationship is valid. This point corresponds closely with the fiber-saturation point of wood as obtained by several other means.
The moisture content of wood in equilibrium with 100 percent relative humidity has never been accurately determined because of the tremendous effect of slight changes in temperature, but the extrapolation, to equilibrium values, of similar data for several different high humidities gave 32 percent as the average value for the fiber-saturation point of seven different species at room temperature. More accurate recent data for Sitka spruce heartwood gave 30.5 as the fiber-saturation point at 27° C. Myer and Rees obtained fiber-saturation points, from shrinkage measurements, and similar shrinkage data of the U. S. Forest Products Laboratory give fiber-saturation point for Sitka spruce, by radial shrinkage of 28 percent and, by tangential shrinkage, of 30 percent. Though such measurements give the correct order of magnitude of the fiber-saturation points, they are complicated by the fact that the shrinkage is not entirely transmitted to the external dimensions of a block of wood. The fact that determinations of the fiber-saturation point by the shrinkage method often give different values for radial and for tangential determinations indicates an inherent lack of accuracy in the method; for the species under discussion (Sitka spruce), however, the average of the radial and the tangential determinations (28 and 30) is exactly equal to the electrical conductivity determination (29.0).

Values for the fiber-saturation point comparable to all of the preceding were obtained by Tiemann of the U. S. Forest Products Laboratory, by means of mechanical strength studies. The mechanical strength properties of wood are not affected by drying until the fiber-saturation point is reached. Below this value of moisture content most of the strength properties increase with a decrease in moisture content. Crushing strength data secured by Tiemann gave fiber-saturation points, for six species at room temperature, varying from 20 to 35 percent moisture content. More recent data of this Laboratory indicate the fiber-saturation point of Sitka spruce by means of four different strength measurements—namely, modulus of rupture, stress of elastic limit in bending, maximum crushing strength parallel to the grain, and the elastic-limit stress compression perpendicular to the grain. The fiber-saturation points thus obtained vary from 25 to 27 percent.

Table I shows the four distinct physical properties of wood—namely, hygroscopicity (measured by relative humidity-moisture content equilibrium values), shrinkage, strength, and electrical conductivity—that are dependent upon the moisture content. The fiber-saturation values as determined by the first two are limiting values—that is, values of moisture content for...
100 percent relative humidity and 0 percent shrinkage. The last two involve phenomena that exist on both sides of the fiber-saturation point. The values given for the fiber-saturation point represent in each case the moisture content corresponding to the limit of validity of the straight-line relationship between the amount of water imbibed by the cell wall ("bound" water) and the magnitude of the other property. The agreement of the values determined by the several methods is as good as can be expected, not only because different specimens were used in each case, but because of the effect of other incompletely controllable variables upon the properties studied.

The electrical conductivity method presented in this paper shows the least complication, by other factors, of the four methods mentioned for determining the fiber-saturation point. Table II gives the fiber-saturation point obtained by this means for several different species of wood. As might be expected, the values indicate that the extractives of redwood are less hygroscopic than the wood substance itself, for removing the extractives raises the fiber-saturation point. All of these values for the fiber-saturation point are higher than those given by Myer and Rees. Part of the difference between these values and those of Myer and Rees may be due to the difference in the methods used for locating the point on the graph that represents the fiber-saturation point. Myer and Rees determined the points of maximum curvature of their graphs, whereas the present author determined in each case the point at which the straight-line portion of the logarithmic curve joins the curved portion -- that is, the point where the relationship between moisture content and electrical conductivity commences to deviate from the relationship holding for water imbibed by the cell walls ("bound" water). Further differences between the sets of data may very well be due to the more nearly complete elimination of moisture gradients in this research than in that of Myer and Rees.
Table I.--Fiber-saturation point of Sitka spruce at room temperature as determined at the U. S. Forest Products Laboratory by several different methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Fiber-saturation point</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative humidity-moisture content equilibrium</td>
<td></td>
<td>30.5</td>
</tr>
<tr>
<td>Shrinkage:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Tangential</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Strength:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus of rupture</td>
<td></td>
<td>27&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Stress at elastic limit in bending</td>
<td></td>
<td>25&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum crushing strength parallel to the grain</td>
<td></td>
<td>27&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Elastic limit stress compression perpendicular to the grain</td>
<td></td>
<td>27&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td></td>
<td>29.0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Indicated values.

Table II.--Fiber-saturation points of wood at 24° to 27° C. as determined by electrical conductivity

<table>
<thead>
<tr>
<th>Species of wood heartwood specimens</th>
<th>Condition of wood</th>
<th>Fiber-saturation point</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redwood</td>
<td>Green</td>
<td></td>
<td>29.5</td>
</tr>
<tr>
<td>Redwood</td>
<td>Resoaked</td>
<td></td>
<td>29.5</td>
</tr>
<tr>
<td>Redwood</td>
<td>Hot-water extracted</td>
<td></td>
<td>31.0</td>
</tr>
<tr>
<td>Redwood</td>
<td>Alcohol extracted</td>
<td></td>
<td>31.0</td>
</tr>
<tr>
<td>Sitka spruce</td>
<td>Resoaked</td>
<td></td>
<td>29.0</td>
</tr>
<tr>
<td>Alaska cedar</td>
<td>Resoaked</td>
<td></td>
<td>28.5</td>
</tr>
<tr>
<td>Western red cedar</td>
<td>Resoaked</td>
<td></td>
<td>30.0</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>Resoaked</td>
<td></td>
<td>30.5</td>
</tr>
<tr>
<td>Western yellow pine</td>
<td>Resoaked</td>
<td></td>
<td>30.0</td>
</tr>
<tr>
<td>Red fir</td>
<td>Resoaked</td>
<td></td>
<td>30.0</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>Resoaked</td>
<td></td>
<td>30.5</td>
</tr>
<tr>
<td>Yellow poplar</td>
<td>Resoaked</td>
<td></td>
<td>31.5</td>
</tr>
</tbody>
</table>

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Fig. 1.—Effect of moisture content on the specific electrical conductance of nonextracted redwood.

- Green, ○ Same specimen oven dried and resoaked.
- Green, □ Same specimen oven dried and resoaked.

Log of specific electrical conductance per cm.

Moisture content in per cent
Fig. 2.—Effect of moisture content on the specific electrical conductance of extracted redwood.