EFFECT OF MOISTURE CHANGES ON THE SHRINKING, SWELLING, SPECIFIC GRAVITY, AIR OR VOID SPACE, WEIGHT AND SIMILAR PROPERTIES OF WOOD

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EFFECT OF MOISTURE CHANGES ON THE SHRINKING, SWELLING, SPECIFIC GRAVITY,
AIR OR VOID SPACE, WEIGHT AND SIMILAR PROPERTIES OF WOOD

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Introduction

Normal wood has a cellular structure that contains wood substance, air space (voids), and more or less water in the cell walls. Different kinds and different amounts of chemical extractives may also be present depending upon the species and upon whether the wood is sapwood (the living part of the tree before it is cut) or heartwood (the nonliving portion that is surrounded by the sapwood).

When green wood is dried or when seasoned wood absorbs water, various physical characteristics are changed, such as the cross-sectional dimensions, density or specific gravity, amount of air or void space, and weight per unit volume. The purpose of this paper is to discuss the relations of the more important variables of this kind and to present graphic methods and formulas that can be easily applied in finding the value of these properties for different woods under different moisture conditions.

This information has various fields of application. For example, it may be desirable to select wood that will have a given density at some particular moisture content or to know the approximate amount of shrinking or swelling that will occur in any given range of moisture change in a particular species. It may also be of interest to compare the relative shrinkage or swelling of different woods. Since the weight affects shipping costs, timber producers and dealers are generally concerned with the weight of the wood under different moisture conditions, while kiln operators and others may be interested in

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1 Original published August 1944.
2 Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
the amount of shrinkage that can be expected and in the amount of water that must be removed in seasoning material of a given species. In the treatment of wood with preservatives or fireproofing chemicals it is sometimes desirable to know the approximate amount of air space in the treated wood so that absorption limitations can be determined.

For convenience, all formulas that have been derived and a list of symbols used in them are given in the appendix. Illustrative examples are also given in the appendix showing how the formulas are employed. The various figures shown make it possible to determine many of the results without using the formulas.

Moisture Content

The amount of water contained in a piece of wood is termed the moisture content. In green timber this water is often referred to as sap; but, since sap may contain small quantities of organic and mineral substances, it is more satisfactory to designate the liquid that can be evaporated as the water or moisture in the wood. The moisture content of the sapwood is usually higher than that of the heartwood, and the differences are generally greater in the conifers or softwoods than in the hardwoods. This is shown by the data in table 1 that gives the average moisture content found in trees of the species listed.

Moisture content is commonly expressed as a percentage of the weight of the oven-dry wood as shown in formula (1) in the appendix. The weight when oven-dry is usually obtained after drying the wood sample in a drying oven at a temperature of about 100° to 105° C. (212° to 221° F.) until the weight becomes constant. If the wood contains volatile substances that can be distilled at the drying temperature, some of these substances will be included with the water removed. The amount of such products that can be distilled in the range of the drying temperatures named, however, is usually so small that it can be neglected.

While it is almost universal practice to base the moisture content on the weight of the oven-dry wood, pulp and paper chemists and others sometimes prefer to use the total or original weight as the base. Formula (2) shows the method of computing the moisture content on the latter basis, and formulas (3) and (4) show the method of changing from one base to the other. Figure 1 shows the relation of the moisture content based on the weight of wood when oven-dry and the moisture content based on the original weight and can be used to change from one base to another without computation. To avoid making this chart too long part of the curve is plotted from right to left, and values of M for this portion are to be read from the upper horizontal scale.

There are several important advantages obtained by computing the moisture content on the basis of the weight of wood when oven-dry. For example, on this basis the moisture content in equilibrium with a given temperature and relative humidity is a fairly definite figure regardless of the specific gravity, but
has no consistency when based on the total weight of wood and water. In addition, the moisture content expressed as a percentage of the weight when ovendry gives a straight line relation between shrinkage and moisture content. Another advantage is that it shows the number of parts of water by weight to the number of parts of ovendry wood substance. To illustrate, if a piece of wood has a moisture content of 40 percent, there are 40 parts of water by weight to 100 parts of wood substance. If the weight is measured in pounds, the piece of wood has 0.40 pound of water per pound of ovendry wood; and if the weight is measured in grams, each gram of ovendry wood has 0.40 gram of water.

Figure 2 shows the pounds of water per cubic foot when the wood has different amounts of moisture and different specific gravities, and figure 3 shows the gallons of water per cubic foot in wood having any given specific gravity and moisture content. Water in the cell walls is under compression and occupies a somewhat smaller volume in the wood than when it has been removed. Figure 3, however, shows the gallons of water held by the wood neglecting the compressive effect of adsorption. Figure 3 shows the percent of total volume occupied by water when the wood has various amounts of moisture and any given specific gravity. In the preparation of figure 4 it was necessary to take into account the higher density of the water in the cell walls since a given weight of the higher-density water will occupy a smaller volume. The relation of water density and moisture content will be discussed under the subject of specific gravity.

Figure 4 will be found convenient to use in finding the space occupied either by wood substance or water, at any moisture content, and also furnishes a means of finding adsorption limitations when the moisture content and specific gravity are known. If the water in the wood cells occupied the same volume as at atmospheric pressure, the percentage of total volume filled with water would be expressed by the relation $P_w = MS$ where $P_w$ is the percent total volume filled, $M$ is the percent moisture, and $S$ is the specific gravity. When the water is compressed to a density $\rho$, as it is in the wood cell walls, the percentage of total volume filled is less for the same moisture content and

$$P_w = \frac{MS}{\rho}.$$  

Figure 4 can also be used to find the volume occupied by wood substance (wood without any water or air space in it) and the void volume or air space at any given moisture content. The diagonal straight line sloping downward to the right and indicated as showing the maximum amount of water the wood will hold with all air space filled, shows the percent of space occupied by water plus the percent of air space if the wood is not completely saturated. The difference between 100 percent and this limiting value is the percent of the total volume occupied by wood substance. For example, assume the wood has a specific gravity of 0.6 and a moisture content of 15 percent. From the chart it is found that the vertical line from this specific gravity intersects the diagonal line at about 59 percent. The volume occupied by wood substance would then be
(100 - 59) or 41 percent. Figure 4 shows that the water (15 percent moisture) occupies about 8 percent of the total volume; hence, the air space is (59 - 8) or 51 percent.

Pure hydrocarbon oils are not absorbed by wood substance and therefore cause no swelling when timbers are impregnated with them. Preservatives, such as the creosotes, are absorbed to a small extent by wood substance, but the resultant swelling is so slight that for practical purposes it can be neglected. When wood is treated with water solutions swelling will, of course, occur, and this swelling must be taken into account in calculating the available air space. The use of figure 4 is illustrated in examples given at the end of this paper.

The Fiber-Saturation Point

When water is absorbed by wood it is first taken up by the cell walls until they become saturated. The point of saturation of the cell walls is known as the fiber-saturation point, and the water contained in the cell walls is designated as hygroscopic, or adsorbed water. Water contained in the fibers after the cell walls have become saturated is held in the lumina, or cell cavities, and is known as free water. Attention was first directed to the fiber-saturation point by H. D. Tiemann and is discussed by him in Forest Service Bulletin 70, "Effect of Moisture Upon the Strength and Stiffness of Wood," (issued in 1906, now out of print).

Various methods have been employed at the Forest Products Laboratory to determine the moisture content (expressed as a percentage of the weight of the oven-dry wood) at which the fiber walls are saturated \((2, 3, 4)\).\(^2\)

Results of these tests show that among the more important factors affecting the moisture content at the fiber-saturation point are temperature, chemical substances in the cell or fiber walls, and chemical composition of the wood. The moisture content at the fiber-saturation point usually ranges from about 25 to 35 percent depending both on the methods by which it is determined and on factors such as those named. In general, an increase of 1° C. (1.8° F.) will reduce the moisture content at the fiber-saturation point about 0.1 of 1 percent. Variations caused by differences in species would probably be in the range of 4 to 5 percent. When the moisture content is reduced below the fiber-saturation point shrinkage will occur depending on the amount of water removed. Likewise, when water is absorbed by dry wood the wood will swell, and the extent of swelling will naturally depend on the same factors that affect shrinkage. No change in dimensions will take place, however, when moisture changes occur well above the fiber-saturation point except under conditions where collapse occurs. Experiments indicate that for use in calculations, assuming normal

\(^2\) Numerals in parentheses refer to publications named in the list of references at the end of this report.
wood temperatures, a good average value for the moisture content at the fiber-saturation point is about 30 percent on a weight basis. The ratio of this value to the average density of water in the cell walls at 30 percent moisture has been used for various calculations of shrinkage, swelling, and specific gravity.

**Shrinkage and Swelling**

The extent to which wood swells or shrinks depends largely on the density and the change in moisture content. If wood were a stress- and strain-free substance, like a gelatine gel, there would be no variation of shrinkage and swelling with change in specific gravity. The variation occurs because there is practically no change in lumen area when shrinkage and swelling take place.

When wood seasons the free water in the cell cavities evaporates until the fiber-saturation point is reached. Further moisture reduction must take water from the cell walls, and it is at this stage that shrinkage starts. In the process of seasoning, a moisture gradient is established from the surface to the interior portion, and the wood near the surface may have a moisture content well below the fiber-saturation point while that at the interior may be at a moisture content considerably above the fiber-saturation point. The amount of moisture present at different distances from the surface depends on a number of variables, such as cross-sectional dimensions, time the wood has been seasoning, species, seasoning conditions, whether sapwood or heartwood, and original moisture content. It is generally understood that when the moisture content of a piece of wood is given, the figure represents the average moisture content of the piece unless otherwise stated.

No moisture changes can take place in a piece of wood unless there is a moisture gradient or a combined relative humidity -- moisture content gradient. Those who are not familiar with this fact sometimes claim that they are able to maintain a uniform moisture content throughout the timber when seasoning by means of heat and changing humidity conditions. This is as much an impossibility as it would be to make an electric current flow in a conductor with no difference in potential along the conductor, or to make water flow by gravity in a stream and maintain the water surface at the same level. Whenever the moisture distribution becomes uniform or, in other words, when the wood has reached a point of moisture equilibrium, no further moisture movement will take place until conditions are changed so that a moisture gradient is set up. This could be done, for example, by changing the surrounding humidity conditions to which the timber is exposed. The rate of seasoning is a function of the moisture gradient, for the rate becomes increasingly slower as the difference in moisture content between the surface and interior becomes smaller.

Figure 5 shows the equilibrium moisture content of wood for different temperatures and different humidity conditions.
Shrinkage takes place chiefly in the radial and tangential directions, that is, at right angles to and parallel to the annual rings. Roughly the ratio of radial to tangential shrinkage is about 1 to 2, but this ratio may vary considerably depending on the species.

Longitudinal shrinkage is very slight (between 0.1 and 0.2 percent \((6)\)) in normal wood and for such material may be considered negligible. The volumetric shrinkage of hardwoods ranges from about 12 to 18 percent in seasoning from the green to the oven-dry condition, while the corresponding shrinkage of the conifers or softwoods usually ranges from about 8 to 14 percent. Since air-dry wood usually has about 12 to 15 percent moisture, shrinkage to the air-dry condition is only about half as much as to the water-free or oven-dry state. The range of volumetric shrinkage of air-seasoned hardwoods is about 6 to 9 percent and that of the softwoods about 4 to 7 percent.

Table 2 shows the average radial, tangential, and volumetric shrinkage from the green to the oven-dry state for various commercial species. Similar data for other woods can be found in U. S. Dept. Agr. Bul. 479 \((1)\). For practical purposes it will be sufficiently accurate to assume that the shrinkage is directly proportional to the change in moisture content below the fiber-saturation point; hence, if \(F\) represents the percent shrinkage shown in table 2, the average percent shrinkage obtained in seasoning to any given moisture content \(M\) below the fiber-saturation point would be computed from the relation:

\[
\text{Shrinkage} = F \left(1 - \frac{M}{30}\right)
\]

For example, assume it is desired to determine the approximate percent radial, tangential, and volumetric shrinkage to be expected in seasoning longleaf pine from the green condition to 12 percent moisture. From table 2 the average radial shrinkage is given as 5.1 percent; the average tangential as 7.5; and the average volumetric as 12.2 percent. Substituting these respective values for \(F\) in the foregoing equation the percent radial shrinkage would be computed as 5.1 \((1 - \frac{12}{30}) = 5.1 \times 0.6 = 3.1\) percent. Similarly the tangential shrinkage would be computed as 7.5 \((0.6) = 4.5\) percent, and the volumetric shrinkage would be 12.2 \((0.6) = 7.3\) percent.

Figure 6 shows the computed volumetric shrinkage, from the green to the oven-dry condition, for woods having different specific gravities based on weight when oven-dry and volume when green. These values are computed on the assumption that shrinkage is proportional to the reduction in moisture content. There are some species that shrink either less or more than they should on this basis, but for a large proportion of the woods the figure shows the approximate amount of shrinkage that could be expected for woods having specific gravities within the range shown.

Since changes in the specific gravity of wood depend on shrinkage or swelling, the relation of these variables will be discussed under the subject of specific gravity.
Specific gravity is commonly known as the ratio of the density of a given substance to the density of a standard substance at some standard temperature. Expressed in another way, it is the ratio of the weight of a material to the weight of another material of equal volume, taken as a standard. The standard for solids and liquids is generally water at maximum density (4°C.). Since density is the mass of matter per unit volume, the numerical values for specific gravity and density are the same in the C.G.S. system. In other systems of measurement, however, the density is expressed in the units employed. For example, in the English system the density of water is 62.42 pounds per cubic foot although the specific gravity is unity as it is in the C.G.S. system.

The specific gravity of wood is usually defined as the ratio of the weight when ovendry of a given volume of wood at the current moisture content, to the weight of an equal volume of water at its maximum density (4°C.). This is defined algebraically in equation (6) in the appendix.

It must be borne in mind that although the original volume will shrink in ovendrying, the volume must be measured when the wood is at the current moisture content M and not after ovendrying or after the moisture content has been changed. It is only when the specific gravity based on weight when ovendry and volume when ovendry is desired that the volume is measured after ovendrying. When the volume is measured at the current moisture content the weight of the wood when ovendry can be determined from the relation, \( W_d = W_w S \) where \( W_d \) is the weight when ovendry per unit volume, \( W_w \) is the weight of a unit volume of water, and \( S \) is the computed specific gravity at this moisture content. If it is desired to determine the moisture content as well as the specific gravity of a wood section, the volume and weight should be determined as soon as the piece is cut. The sample can then be ovendried and again weighed after drying. The weight when ovendry would be used in computing both the moisture content and the specific gravity as indicated in equations (1) and (6).

There are some who prefer to compute the specific gravity of the wood as the ratio of the original weight of the wood before ovendrying to the weight of an equal volume of water. This value of specific gravity is, of course, larger than that based on the weight when ovendry. If this is represented by \( S_o \) and the specific gravity based on weight when ovendry by \( S \), then \( S_o = S \left(1 + \frac{M}{100}\right) \) where \( M \) is the moisture content of the wood when the volume measurement is made.

Since the density or specific gravity of wood increases as the wood shrinks in seasoning, there is a gradual increase in specific gravity when wood seasons from the fiber-saturation point or below to the ovendry condition. This change in specific gravity will depend on the species as well as on the degree of seasoning, since the heavier woods will shrink more than the lighter ones over the same range of moisture content. The relation of specific gravity and shrinkage can be illustrated as follows:
Since the longitudinal shrinkage of wood is so small that its effect on volume changes can be disregarded, only changes in the cross-sectional area will be considered in this discussion. Assume a wood section W inches wide and H inches thick is cut from a green timber, and after ovendrying the width is \((W - a)\) inches and the thickness is \((H - b)\) inches. The volumetric shrinkage = original volume minus volume after drying.

\[
\text{Dividing this by WH gives the shrinkage per unit volume}
\]

\[
= \left[ \frac{1 - \frac{(W - a)(H - b)}{WH}}{WH} \right]
\]

If \(V_g\) = the original volume \(WH\); \(V_d\) = the volume after shrinkage, which is \((W - a)(H - b)\); \(S\) = the specific gravity of the green wood with volume \(WH\); and \(S_d\) = the specific gravity of the ovendried wood with volume \((W - a)(H - b)\), then \(S_g(V_g) = S_d(V_d)\) or, \(S_g = S_d = \frac{V_d}{WH} = \frac{(W - a)(H - b)}{WH} = (1 - \text{shrinkage per unit volume})\). From this relation \(S_g = S_d (1 - \text{shrinkage per unit volume})\). If \(C = \text{the shrinkage per unit volume, } S_g = S_d (1 - C)\). The shrinkage \(C\) expressed in terms of \(S_g\) and \(S_d\) is then \(\frac{S_d - S_g}{S_g}\).

If the wood swells from the ovendry condition to the fiber-saturation point, the swelling \((E)\) per unit volume equals the foregoing equation (A) divided by \((W - a)(H - b)\). This gives

\[
\left[ \frac{WH}{(W - a)(H - b)} - 1 \right] = \left[ \frac{1}{1 - C} - 1 \right] = E.
\]

Then \(\frac{S_d}{S_g} = \frac{V_g}{V_d} = \frac{WH}{(W - a)(H - b)}\) or \(S_g (1 + E) = S_d\). The swelling \(E\) in terms of \(S_g\) and \(S_d\) is then \(\frac{S_d - S_g}{S_g}\).

From the relations shown for shrinkage and swelling and shrinkage expressed in terms of the swelling is \(C = \frac{E}{1 + E}\); and the swelling in terms of shrinkage is, \(E = \frac{C}{1 - C}\), where \(E\) is the swelling and \(C\) is the shrinkage, each expressed as a decimal fraction.

Rept. No. 1448 -8-
The connection between specific gravity and volume change is shown by equations (24) and (27) in the appendix, when the moisture content changes between values of $M_1$ and $M_2$. Equations (22) to (29) in the appendix follow from the foregoing relations shown for shrinkage, swelling, and specific gravity.

Although the change in specific gravity that occurs as wood seasons is not strictly linear, it is sufficiently accurate for practical purposes to assume that it increases in direct proportion to the loss of moisture below the fiber-saturation point. The lowest specific gravity will, of course, be that based on the weight when oven-dry and the volume when green; the maximum value will be that based on the weight when oven-dry and volume when oven-dry. When these two values of specific gravity are known the approximate average specific gravity based on the weight when oven-dry and volume at any moisture content can be computed from the simple relation shown by equation (8) in the appendix. This formula is convenient to use when the average specific gravity values $S_g$ and $S_d$ are known. These specific gravity values are given for native species in U. S. Dept. Agr. Tech. Bul. 479 (1).

It is important to keep in mind that the specific gravity of wood may vary more or less in the same timber or in timbers of the same species because of differences in growth conditions and variations in degree of seasoning at different parts of the timber. Specific gravity values, like those of moisture content, are, therefore, only approximate and may vary to an appreciable extent.

Experiments made at the Forest Products Laboratory (5) show that for most of the softwoods and many of the hardwoods the volumetric shrinkage is about proportional to the change in moisture content that occurs in seasoning. The shrinkage differences for a large proportion of the woods are usually small when the specific gravities of the green woods are the same, although there are exceptions in this respect.

The principal exceptions among the species listed in table 2 are American basswood, cottonwood, pecan, honeylocust, black locust, eastern redcedar, sweetgum, redwood, Engelmann spruce, and black walnut.

Stresses such as cause collapse of the cells in seasoning (7) and extractives in the cell walls affect shrinkage. Collapse will cause increased shrinkage, while infiltrating chemicals usually have the opposite effect. The differences between the computed and measured average volumetric shrinkage (absolute basis) for the woods named ranges from about 2 to 3 percent, except honeylocust, cottonwood, and eastern redcedar, which have a shrinkage difference ranging from about 4 to 5 percent, and basswood and black locust, which are outstanding in shrinkage variations. Because of collapse of the cell walls the difference between the computed and measured volumetric shrinkage of basswood is about 7 percent. In other words, this species shrinks over 80 percent more than woods of the same specific gravity normally shrink. On the other hand, extractives in the heartwood of black locust reduce the shrinkage to about 55 percent of the amount that usually occurs in woods of corresponding density.
For general purposes, however, one may compute the approximate shrinkage and specific gravity on the basis of moisture loss from the cell walls. The unit volumetric shrinkage $C$, expressed as a decimal fraction, would then be computed from the relation,

$$C = S_g \left( \frac{1}{1.113} \right) \left( \frac{30 - M}{100} \right),$$

or since $\frac{1}{1.113}$ is approximately 0.9, this becomes,

$$C = S_g (0.9) \left( \frac{30 - M}{100} \right)$$

In this expression $S_g$ is the specific gravity based on weight when ovendry and the volume when green, $M$ is any moisture content between the fiber-saturation point and the ovendry condition, and 1.113 is the density of the water in the fiber walls when they are saturated.

If $S_a$ represents the specific gravity at any moisture content $M$ below the fiber-saturation point,

$$S_a = \frac{S_g}{1 - C} = \frac{S_g}{1 - S_g (0.9) \left( \frac{30 - M}{100} \right)}$$

Figure 7 shows the computed change in specific gravity from the green to the ovendry condition, for different values of specific gravity based on the weight when ovendry and volume when green. Values of $S_a$ and $S_d$ are read from the left-hand scale. From this chart it is possible to obtain the specific gravity based on weight when ovendry and volume at current moisture content when the current moisture content and the specific gravity based on weight when ovendry and volume when green are known. It is also possible, if the specific gravity at some particular moisture content is known, to determine the computed specific gravity at any other moisture content. The dotted line with arrows illustrates how to find the computed specific gravity at 12 percent moisture when the specific gravity based on weight when ovendry and volume when green is assumed to be 0.55. The specific gravity at 12 percent moisture is shown on the left-hand scale as 0.604 or approximately 0.60. If, on the other hand, the specific gravity at some particular moisture content is known or assumed, the computed specific gravity at any other moisture content can be readily found. For example, assume the specific gravity of a wood at 8 percent moisture is 0.45. Passing from 0.45 on the left-hand scale to the vertical line from 8 percent moisture it is found that the point of intersection is between the lines for specific gravity values (based on weight when ovendry and volume when green) of 0.40 and 0.42; hence, the specific gravity based on the weight when ovendry and volume when green would be slightly over 0.41 for this wood. If the specific gravity at 15 percent moisture is required for this wood, follow between the curves for 0.40 and 0.42 specific gravity to the vertical line from 15 percent moisture. At the same proportional distance (between the curves for 0.40 and 0.42) as the point of intersection for 8 percent moisture, the specific gravity for 15 percent moisture is found to be about 0.44.
It is convenient to use the specific gravity $S_g$ based on weight when oven dry and volume when green in making calculations since seasoned wood soaked in water until it is thoroughly wet will swell to about the green dimensions. The value of $S_g$ can then be determined for the soaked wood. Tables 1 and 2 show average values of $S_g$ for the species listed. The specific gravity based on weight and volume when oven dry can also be used in finding different specific gravity values from the chart. For example, assume $S_d$ (the value based on volume when the wood is oven dry) is 0.54 and it is desired to find the specific gravity $S_g$ and also the specific gravity at 15 percent moisture content, $S_m$. The value 0.54 is found on the left-hand scale of figure 7 and lies between the curves for $S_g = 0.46$ and 0.48. The value of $S_g$ is thus slightly over 0.47. By following at the same proportional distance between the two lines for $S_g$ equals 0.46 and 0.48 the specific gravity at 15 percent moisture content is found to be slightly over 0.50. The procedure is shown in figure 7 by the dotted line from 0.54 (left-hand scale) to the vertical line from 15 percent moisture content. Note that the specific gravity at 15 percent moisture content is read on the left-hand scale directly across from the point of intersection with the vertical line.

Figure 8 shows the relation of original weight, moisture content, and the specific gravity based on weight and volume when oven dry. The value of $S_d$ is found when the weight and moisture content of the wood have been determined. Data for this chart were computed from formula (15) of the appendix with values of $W_0$ and $M$ assumed. The right-hand portion is a continuation of the part shown on the left. This chart will be found convenient to use where the average moisture content can be determined with a moisture meter. The chart shows weights both in grams per cubic centimeter and in pounds per cubic foot. The following example will illustrate the use of this chart:

Assume the average moisture content of a stick is 14 percent and the weight is 27 pounds per cubic foot, and it is desired to find the specific gravity this wood should have in the oven dry condition. Each weight line differs from the next lower by 1.25 pounds, hence, 1/5 the distance between any two lines represents 0.25 pounds. Directly across on the left-hand scale from a point 3/5 the distance between the lines for 26.25 and 27.50 pounds (measured on the line for 14 percent moisture) the specific gravity value $S_d$ is found to be about 0.40, which is the value to be determined. The corresponding specific gravity $S_g$ can be found by means of figure 7. From this figure it is found that when $S_d = 0.40$ (on the left-hand scale) the value of $S_g$ is about 0.36. This can also be computed by means of formula (16) in the appendix.

**Specific Gravity of Wood Substance**

For various calculations it is necessary to know the specific gravity of wood substance. This value is fairly constant for all species.
A given volume of oven-dry wood normally contains a large amount of air space or void volume because of the cellular structure, but the volume occupied by wood substance alone is considerably less than the volume occupied by wood in the usual form in which it grows. A certain amount of compression occurs in the water adsorbed by the cell walls, and the density or specific gravity of wood substance determined in water is therefore somewhat higher than when measured in a substance that is not compressed by the force of adsorption. In experiments made by Stamm (2, 3) at the Forest Products Laboratory he first used benzene to avoid the compression of the medium in which the density of wood substance was determined. Some difficulty was experienced in getting this liquid to penetrate the cell walls effectively, but later he overcame the difficulty by using helium gas as the medium. Results of these experiments showed that the density of wood substance measured in helium gas was about 1.46, while an average value of the density determined in water was about 1.53. From these results the true specific volume of wood substance is 1/1.46 or about 0.685, while the apparent specific volume in water is 1/1.53 or about 0.654, a difference of 0.031. The following values of water density in the cell walls were determined in the experiments with helium gas to which reference has been made:

<table>
<thead>
<tr>
<th>Moisture Content (M)</th>
<th>Density of Water (ρ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.244</td>
</tr>
<tr>
<td>10</td>
<td>1.202</td>
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<tr>
<td>15</td>
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<td>20</td>
<td>1.144</td>
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<tr>
<td>25</td>
<td>1.127</td>
</tr>
<tr>
<td>30</td>
<td>1.113</td>
</tr>
</tbody>
</table>

Figure 9 shows the water density plotted against moisture content up to the fiber-saturation point. Above the fiber-saturation point the average density of the total water in the wood can be found for any moisture content from the relation, $ρ = \frac{M}{M - 3.1}$ where $M$ is the percent moisture and the factor 3.1 is the difference in moisture content on the volume and weight basis, at the fiber-saturation point.

Relation of Weight of Wood, Weight of Water in Wood, and Moisture Content

From equation (1) in the appendix, for the moisture content of wood, it is found that the equation for the oven-dry weight is

$$W_d = W_o + (1 + \frac{M}{100})$$
The weight of water per unit volume is determined from equation (17) or (17a), while the percentage of volume occupied by water is found by equations (18) and (18a).

In round timbers the proportion of sapwood can be computed from formula (21) where D is the average diameter of the timber and t is the average thickness of sapwood. After the proportion of sapwood is determined the total weight of the timber can be computed from formula (20) or (20a). In green round timbers the sapwood often has a much higher moisture content than the heartwood, and the average moisture content of each should be determined separately. Air-seasoned timbers, on the other hand, may have a higher average moisture content in the heartwood if the sapwood has had an opportunity to lose a considerable amount of moisture. Seasoning might also cause a significant difference in the specific gravity of the sapwood and heartwood if there was much difference in the moisture content of the wood near the surface and that at the interior.

Figure 10 shows the relation of moisture content, specific gravity, and weight of wood in pounds per cubic foot. The specific gravity values shown are based on weight when oven-dry and volume when green. Weights below the fiber-saturation point were determined from specific gravity values computed by means of formula 9 in the appendix. It may be noted that for the more dense woods the change in weight below the fiber-saturation point is small because of the increase in density which, to a large extent, offsets the decrease in weight because of loss in moisture.

Figure 11 shows three curves, one the maximum moisture content that wood of any specific gravity could hold with all air space filled, another shows the weight of oven-dry wood in pounds per cubic foot, and the third the weight of water in pounds per cubic foot. The dotted lines with arrows show the method of using the chart. In this illustration the specific gravity of the wet wood is assumed to be 0.45. At the point of intersection with the curve for maximum moisture content the maximum amount the wood will hold is read from the left-hand scale as about 157 percent. From the intersection with the line showing the weight of oven-dry wood the weight is shown on the right-hand scale to be about 28 pounds. Similarly from the point of intersection with the line showing the weight of water the weight is found from the right-hand scale to be about 44 pounds per cubic foot. Since this figure shows data for saturated wood, all specific gravity values are those based on oven-dry weight and volume when green.

Relation of Specific Gravity, Moisture Content, and Air Space in Wood

Equations (30) and (31) in the appendix show the method of calculating the air space in wood. Formula (30) will apply for any moisture content either above or below the fiber-saturation point. Since the average density of the water in the wood is determined from the equation

\[ \rho = \frac{M}{M - 3.1} \]

Rept. No. 1448
when the moisture content is at or above the fiber-saturation point and M is the total moisture content, equation (30) can be written as shown in (31). It may be noted that in the last form of (31) the specific gravity of wood substance as determined in water (1.53) can be substituted for 1.46, the value determined in helium gas, which makes it unnecessary to subtract 3.1 from the moisture content M.

Figure 12 shows the percentage of air space in wood having moisture content values up to 200 percent and specific gravities ranging from 0.12 to 1.08, based on the weight when oven-dry and the volume at current moisture content. For example, a wood having a specific gravity of 0.5 when the moisture content is 10 percent would have nearly 62 percent air space, while another wood having the same specific gravity based on weight when oven-dry and green volume and a moisture content of 65 percent would have about 35 percent air space. The effect of adsorption on the volume occupied by water in the cell walls has been taken into account in the calculations of air space.
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APPENDIX

Symbols Used in Formulas

C = Shrinkage per unit volume (expressed as a decimal fraction).

D = Average diameter of timber in inches.

E = Swelling per unit volume (expressed as a decimal fraction).

M = Percentage moisture based on oven-dry weight.

m = Percentage moisture based on original weight.

$M_1$ and $M_2$ = Percentage moisture content below the fiber-saturation point where moisture content range is $M_1$ to $M_2$ and $M_1$ is less than $M_2$.

$M_r$ = Maximum percentage moisture wood will hold when all void space is filled with water.

$M_h$ = Percentage moisture of heartwood (when considered separately from that of the sapwood) based on oven-dry weight.

$M_s$ = Percentage moisture of sapwood (when considered separately from that of the heartwood) based on oven-dry weight.

P = Percentage air space in wood.

$P_w$ = Percentage volume occupied by water in wood.

$R_s$ = Percentage sapwood in timber based on total volume.

$\rho$ = Density of water in wood.

S = Specific gravity based on the weight when oven-dry and volume at current moisture content.

$S_a$ and $S_b$ = Specific gravity values when wood has moisture contents of $M_1$ and $M_2$, respectively. $S_a$ greater than $S_b$ and $M_1$ less than $M_2$.

$S_d$ = Specific gravity based on the weight of the oven-dry wood and volume when oven-dry.
\( S_g \) = Specific gravity based on the weight of the ovendry wood and volume when green.

\( S_h \) = Specific gravity of heartwood (when considered separately from that of the sapwood).

\( S_o \) = Specific gravity based on the original weight and volume at current moisture content = \( S \left( 1 + \frac{M}{100} \right) \).

\( S_s \) = Specific gravity of sapwood (when considered separately from that of the heartwood).

t = Average thickness of sapwood in inches.

\( W \) = Original weight of moisture specimen.

\( W_a \) = Weight of moisture specimen when ovendried.

\( W_d \) = Weight of ovendry wood per unit volume at moisture content \( M \).

\( W_m \) = Weight of water in wood at moisture content \( M \) (weight per unit volume).

\( W_o \) = Weight per unit volume of wood at moisture content \( M \) = weight per unit volume of wood before ovendrying.

\( W_w \) = Weight per unit volume of water at maximum density. \( (W_w = 1 \text{ in C.G.S. system and equals } 0.0361 \text{ pound per cubic inch or } 62.4 \text{ pounds per cubic foot in the English system.)} \)

1.46 = Specific gravity of wood substance determined in helium gas.

1.53 = Specific gravity of wood substance determined in water.

**Formulas**

**Moisture Content in Percent**

Moisture content based on weight when ovendry = \( M \)

\[
M = 100\left( \frac{W - W_a}{W_a} \right) = 100\left( \frac{W_o - W_d}{W_d} \right) = 100\left( \frac{W_o}{W_d} - 1 \right) = 100\left( \frac{W_o}{S(W_w)} - 1 \right) \quad (1)
\]

Rept. No. 1448
Moisture content based on original weight (weight before ovendrying) = \( m \)

\[
m = 100\left(\frac{W_o - W_d}{W_o}\right) = 100\left(1 - \frac{W_d}{W_o}\right) \tag{2}
\]

\( M \) expressed in terms of \( m \)

\[
M = \frac{100m}{100 - m} \tag{3}
\]

\( m \) expressed in terms of \( M \)

\[
m = \frac{100M}{100 + M} \tag{4}
\]

Maximum Moisture Content in Percent (all air space filled)

\[
M_f = 100 \left[ \frac{W_w - \frac{W_d}{1.53}}{W_d} + W_d \right] = 100 \left[ \frac{1}{S_g} - \frac{1}{1.53} \right] \tag{5}
\]

If the weights are expressed in pounds per cubic foot

\[
M_f = 100 \left(\frac{62.4}{W_d} - \frac{1}{1.53}\right)
\]

Specific Gravity

Specific gravity based on weight when ovendry and volume at current moisture content = \( S \)

\[
S = \frac{W_d}{W_w} = \frac{W_o}{W_w(1 + \frac{M}{100})} \tag{6}
\]

If the weights are expressed in pounds per cubic foot

\[
S = \frac{W_d}{62.4} = \frac{W_o}{62.4 \left(1 + \frac{M}{100}\right)} \tag{6a}
\]

Specific gravity \((S_o)\) based on weight of wood before ovendrying and volume at current moisture content.

\[
S_o = \frac{W_o}{W_w} = S \left(1 + \frac{M}{100}\right) \tag{7}
\]
If the weights are expressed in pounds per cubic foot

\[ S_0 = \frac{W_o}{62.4} \]  \hspace{1cm} (7a)

Specific gravity at any moisture content \( M \), below the fiber-saturation point, determined from specific gravity values based on weight when oven-dry and volume when green and on weight and volume when oven-dry:

\[ S_a = \left[ S_d - (S_d - S_g) \frac{M}{30} \right] \]  \hspace{1cm} (8)

When \( S_a \) and \( S_g \) are known solving for \( S_d \) gives,

\[ S_d = \frac{30S_a - MS_g}{30 - M} \]  \hspace{1cm} (8a)

Specific gravity \( (S_a) \) computed for any moisture content \( M \) below the fiber-saturation point when the specific gravity of the wood at some particular moisture content is known or assumed.

Based on specific gravity of wood when green = \( S_g \)

\[ S_a = \frac{S_g}{1 - S_g (0.009) (30 - M)} \]  \hspace{1cm} (9)

Based on specific gravity of wood when oven-dry = \( S_d \)

\[ S_a = \frac{S_d}{1 + S_d (0.009) M} \]  \hspace{1cm} (10)

If \( M_1 \) is the percent moisture content when the specific gravity is \( S_a \), \( M_2 \) is the percent moisture content when the specific gravity is \( S_b \) and \( M_2 \) is greater than \( M_1 \), then:

\[ S_a = \frac{S_b}{1 - S_b (0.009) (M_2 - M_1)} \]  \hspace{1cm} (11)

\[ S_b = \frac{S_a}{1 + S_a (0.009) (M_2 - M_1)} \]  \hspace{1cm} (12)
If \( W_0 \) is the original weight per unit volume at any moisture content \( M \) between the fiber-saturation point (taken as 30 percent) and the oven-dry condition,

\[
S_d = \frac{W_0}{(1 + \frac{M}{100}) W_w - W_0 (0.009) (M)}
\]  (15)

If \( W_0 \) is in pounds per cubic foot

\[
S_d = \frac{W_0}{(1 + \frac{M}{100}) 62.4 - W_0 (0.009) (M)}
\]

\[
S_g = \frac{W_0}{(1 + \frac{M}{100}) W_w + W_0 (0.009) (30 - M)}
\]  (16)

If \( W_0 \) is in pounds per cubic foot

\[
S_g = \frac{W_0}{(1 + \frac{M}{100}) 62.4 + W_0 (0.009) (30 - M)}
\]

Weight of Water per Unit Volume of Wood

\[
W_m = (W_0 - W_d) = W_d \left( \frac{M}{100} \right) = W_w \left( \frac{MS}{100} \right)
\]  (17)
If the weights are expressed in pounds per cubic foot

\[ W_m = 62.4 \left( \frac{MS}{100} \right) \]  

(17a)

**Percentage of Volume Occupied by Water**

\[ P_w = 100 \left( \frac{W_o - W_d}{W_w} \right) = \frac{MS}{\rho} \]  

(18)

If the weights are expressed in pounds per cubic foot

\[ P_w = 100 \left( \frac{W_o - W_d}{62.4 \rho} \right) \]  

(18a)

Note: Values of \( \rho \) can be found from figure 9 for moisture contents up to the fiber-saturation point. Above the fiber-saturation point

\[ \rho = \frac{M}{M - 3.1} \]  

Substituting this in (18), gives

\[ P_w = (M - 3.1) (S) \]  

when the moisture content \( M \) is at or above the fiber-saturation point.

**Total Weight of Wood and Water at Any Moisture Content**

\[ W_o = W_d (1 + \frac{M}{100}) = S(W_w) (1 + \frac{M}{100}) \]  

(19)

When \( W_o \) and \( W_d \) are in pounds per cubic foot:

\[ W_o = S(62.4) \left( 1 + \frac{M}{100} \right) \]  

(19a)
When the moisture content and specific gravity of the heartwood are to be considered separately:

\[ W_o = W_w \left[ S_s \left( \frac{R_s}{100} \right) \left( 1 + \frac{M_s}{100} \right) + S_h \left( 1 - \frac{R_s}{100} \right) \left( 1 + \frac{M_h}{100} \right) \right] \]  

(20)

\[ = (W_s + W_h) \] where \( W_s \) is the proportional weight of sapwood and \( W_h \) is the proportional weight of heartwood per unit volume.

If the specific gravity of the sapwood (\( S_s \)) is assumed to be the same as the specific gravity of the heartwood, which is usually sufficiently close for green timbers,

\[ W_o = (S) (W) \left[ 100 \left( \frac{R_s}{100} \right) \left( \frac{M_s}{100} - \frac{M_h}{100} \right) + 1 \right] \]  

(20a)

If the weights are expressed in pounds per cubic foot \( W_w = 62.4 \).

Percent Sapwood in Total Volume

\[ R_s = 100 \left( \frac{4t \left( D - t \right)}{D^2} \right) \]  

(21)

Volumetric Shrinkage

Shrinkage per unit volume from green to oven-dry condition,

\[ C = \left( \frac{S_d - S_g}{S_d} \right) \]  

(22)

For shrinkage from the green condition to any moisture content \( M \)

\[ C = S_g (0.9) \left( \frac{30 - M}{100} \right) \]  

(23)
When $S_a$ is the specific gravity of the wood at moisture content $M_1$ and $S_b$ is the corresponding specific gravity at another moisture content $M_2$, the shrinkage in seasoning from $M_2$ to $M_1$ (where $M_2$ is greater than $M_1$ and not over 30 percent, the moisture content taken as the fiber-saturation point).

$$C = \left(\frac{S_a - S_b}{S_a}\right) = S_b \left(0.9 \left(\frac{M_2 - M_1}{100}\right)\right)$$ \hfill (24)

**Volumetric Swelling**

Swelling per unit volume from ovendry to green condition

$$E = \left(\frac{S_d - S_g}{S_g}\right)$$ \hfill (25)

For swelling from the ovendry condition to any moisture content $M$

$$E = S_d \left(0.9 \left(\frac{M}{100}\right)\right)$$ \hfill (26)

When $S_a$ is the specific gravity of the wood at moisture content $M_1$ and $S_b$ is the specific gravity at moisture content $M_2$ the swelling when the moisture content increases from $M_1$ to $M_2$ is determined from the relation

$$E = \left(\frac{S_a - S_b}{S_b}\right) = S_a \left(0.9 \left(\frac{M_2 - M_1}{100}\right)\right)$$ \hfill (27)

Shrinkage in terms of swelling,

$$C = \left(\frac{E}{1 + E}\right)$$ \hfill (28)

Swelling in terms of shrinkage,

$$E = \left(\frac{C}{1 - C}\right)$$ \hfill (29)

**Percentage Air Space in Wood**

If $M_k$ is the percent moisture content at or below the fiber-saturation point (taken as 30 percent) and $M_a$ is the percent moisture content above the fiber-saturation point.
When the moisture content is at or above the fiber-saturation point and $M$ equals $M_k + M_a$, equation (22) may be written

$$P = 100 \left[ 1 - S \left( \frac{1}{1.46} + \frac{M_k}{100(\rho)} + \frac{M_a}{100} \right) \right]$$

(30)

### Examples Illustrating Use of Formulas

**Specific Gravity**

**Example 1** - (Formula 6)

Assume dimensions of wood sample = 2 x 2 inches in cross-section and 1 inch thick; average moisture content = 12 percent; weight of sample = 0.06 pound.

Determine specific gravity $S$.

Volume of sample = 4 cubic inches and oven dry weight $W_d$ = original weight of 0.06 pound divided by $(1 + \frac{M}{100}) = 0.06 \div (1.12) = 0.0536$ pound.

Weight of 1 cubic inch of the wood when oven-dry = $0.0536 \div 4 = 0.0134$ pound.

The weight of 1 cubic inch of water = 0.0361 pound. Substituting $W_d$ and $W_w$ in formula (6) $S = \frac{W_d}{W_w} = 0.0134 + 0.0361 = 0.37$ approximately.

**Example 2** - (Formula 7)

Determine specific gravity $S_o$ using data given in example 1.

$$S_o = \frac{W_o}{W_w} = \frac{0.06}{0.0361} = 0.416 \text{ or about } 0.42.$$

**Example 3** - (Formula 8)

Compute specific gravity $S_a$ when moisture content = 10 percent, specific gravity $S_g = 0.45$ and $S_d = 0.51$. Substituting in formula 8, $S_a$ = specific gravity of wood at 10 percent moisture = $\left[ 0.51 - (0.51 - 0.45) \frac{10}{30} \right] = 0.49$.  

Rept. No. 1448
Example 4 - (Formula 8a)

The specific gravity of a piece of wood at 12 percent moisture content has been found to be 0.38. After soaking in water the specific gravity \( S_g \) = 0.32. Compute the specific gravity \( S_d \). \( S_d = \frac{30(0.38) - 12(0.32)}{30 - 12} = 0.42. \)

Example 5 - (Formula 9)

Compute \( S_a \) when \( S_g = 0.5 \) and moisture content = 12 percent. Substituting in formula (9)

\[
S_a = \frac{0.5}{1 - 0.5(0.009)(30 - 12)} = 0.544 \text{ or about } 0.54
\]

Example 6 - (Formula 10)

Assume \( S_d = 0.56 \). Find specific gravity \( S_a \) when the moisture content is 20 percent.

Substituting in formula (10)

\[
S_a = \frac{0.56}{1 + 0.56(0.009)(20)} = 0.509 \text{ or about } 0.51
\]

Example 7 - (Formula 11)

The moisture content \( M_2 = 18 \) percent and the specific gravity of the wood at this moisture content = 0.55 = \( S_b \). Compute the specific gravity \( S_a \) when the moisture content is 8 percent = \( M_1 \).

Substituting in formula 11,

\[
S_a = \frac{0.55}{1 - 0.55(0.009)(18 - 8)} = 0.579 \text{ or about } 0.58.
\]

Example 8 - (Formula 12)

The specific gravity at 5 percent moisture content (= \( M_1 \)) is 0.46 (= \( S_a \)). Compute the specific gravity \( S_b \) at 15 percent moisture content \( (M_2 = 15) \).

Substituting in formula 12,

\[
S_b = \frac{0.46}{1 + 0.46(0.009)(15 - 5)} = 0.442 \text{ or about } 0.44.
\]
Example 9 - (Formula 15)

A timber weighs 42 pounds per cubic foot = \( W_0 \), and the average moisture content \( M = 16 \) percent. Compute the specific gravity \( S_d \) based on oven-dry weight and volume when oven-dry.

Substituting in formula (15),

\[
S_d = \frac{42}{(1.16)(62.4) - 42(0.009)(30 - 16)} = 0.626 \text{ or about 0.63.}
\]

Example 10 - (Formula 16)

With the same data as in example 9 compute the specific gravity \( S_g \) based on weight when oven-dry and volume when green.

Substituting in formula (16),

\[
S_g = \frac{42}{(1.16)(62.4) + 42(0.009)(16)} = 0.535 \text{ or about 0.54.}
\]

Weight of Water per Unit Volume

Example 11 - (Formula 17)

A timber weighs 48 pounds per cubic foot and the specific gravity \( S \) at the current moisture content is 0.56. Find the weight of water in pounds per cubic foot of wood and the average moisture content. The oven-dry weight \( W_d = (0.56)(62.4) = 35 \) pounds per cubic foot. The weight of water is then \( 48 - 35 = 13 \) pounds per cubic foot and the average moisture content

\[
= \left( \frac{13}{35} \right) 100 = 37 \text{ percent.}
\]

Percentage of Volume Occupied by Water

Example 12 - (Formula 18)

With the data given in example 11 find the percentage of volume occupied by water. Since the moisture content is above the fiber-saturation point,

\[
\rho = \frac{M}{M - 3.1} = \frac{37}{37 - 3.1} = 1.092.
\]
Therefore,\
\[ P_W = \frac{48 - 35}{62.4 \times 1.092} \times 100 = 19 \text{ percent.} \]

The same result is obtained by using formula (18a), since (37 - 3.1)0.56 = 19 percent.

The following examples illustrate the use of figure 4 in calculating absorption limitations for both oils and water solutions. Data for this chart were computed using formula (18).

**Example 13**

Assume the average specific gravity of the wood is 0.55, the average moisture content is 25 percent and it is desired to find how much unfilled space is left in the treated wood when the net retention is 16 pounds of creosote per cubic foot and the preservative weighs 65 pounds per cubic foot. Since swelling caused by the absorption of creosote is very slight there would be no appreciable change in the wood volume and therefore no change in the specific gravity. From figure 4 the percentage volume filled with water, when the wood has a specific gravity of 0.55 and a moisture content of 25 percent, is found to be about 12 percent. The vertical line from 0.55 specific gravity intersects the diagonal line at about 62 percent; hence, the available space would be (62-12) or 50 percent. The preservative will occupy \( \frac{16}{65} \) or 24.6 percent of a cubic foot, and the unfilled space will be (50 - 24.6) or, omitting decimals, about 25 percent. If all the space could be filled with preservative, the maximum absorption would evidently be (65 x 0.50) or 32.5 pounds per cubic foot. Experience shows, however, that it is not possible to fill all the available air space even when the wood is completely penetrated and the treating conditions most favorable for heavy absorptions are employed.

**Example 14**

Assume a timber has a volume of 1.75 cubic feet before treatment and it is desired to find how much of the available void volume or air space is filled with a water solution of fire-retardant chemicals when the total net retention in the timber is 58 pounds and the specific gravity of the solution is 1.12. It will be assumed that the initial moisture content is 10 percent and the specific gravity at this moisture content is 0.50. Under these conditions water is added to the wood during treatment, and it will swell to practically the volume that would be occupied when the timber is green. This, of course,
assumes that the solution has penetrated the entire volume. If \( W_a \) is the weight of the timber after treatment, \( W_b \) the weight before treatment, \( V_a \) the volume after treatment, and \( V_b \) the volume before treatment, the net retention will be \((W_a - W_b)\) and the absorption in pounds per cubic foot will be \((W_a - W_b) + V_a\). Likewise \( V_a = V_b(1 + E) \) where \( E \) is the proportional swelling computed from formula (27), appendix. In this example \( V_b = 1.75 \).

The first step is to compute \( S_g \), the specific gravity based on weight when oven dry and volume when green. Using formula (12), appendix, \( S_b \) corresponds to \( S_g \) and \( S_a \) corresponds to 0.50, the specific gravity of the wood at 10 percent moisture. Substituting in formula (12) and taking the fiber-saturation point of the wet wood as 30 percent = \( M_w \).

\[
S_g = \frac{0.5}{1 + 0.5(0.009)(30 - 10)} = 0.459 \text{ or about } 0.46.
\]

This value could also be found directly from figure 7 by passing horizontally from 0.5 on the left-hand scale to the vertical line from 10 percent moisture. The point of intersection is found close to the curve for \( S_g = 0.46 \).

The second step is to find from formula 18 or figure 4 the volume occupied by 10 percent moisture, when the specific gravity is 0.46, and also find the total void volume. Figure 4 shows that at this specific gravity 10 percent moisture occupies about 4 percent of the total volume. The vertical line from 0.46 specific gravity intersects the diagonal line at about 68.5 percent or, omitting decimals, 68 percent total volume. The volume not occupied by water (original moisture) or wood substance is then \((68 - 4)\) or 64 percent air space. This can also be checked by figure 12 that shows about 64.5 percent air space when the moisture content is 10 percent and the specific gravity is 0.46.

The third step is to compute the swelling \( E \) from formula (27), appendix. Substituting in this formula \( E = \frac{0.5 - 0.46}{0.46} = 0.087 \) or 8.7 percent.

Since the volume after swelling \( V_a = V_b(1 + E) \) the volume \( V_a = 1.75(1.087) = 1.9 \) cubic feet. The total available air space is then \((1.9)(0.64) = 1.22\) cubic feet, approximately.

The net retention was assumed as 58 pounds and since the specific gravity of the solution was 1.12, one cubic foot of solution weighs \((1.12)(62.4)\) or about 70 pounds per cubic foot. The volume occupied by 58 pounds is then \(58 + 70 = 0.83\) cubic foot while the available space was computed as 1.22 cubic feet.
feet. The percentage air space filled is then \( \frac{0.83}{1.22} \times 100 = 68 \) percent. If it were possible to fill all the air space, the absorption would be \((70)(1.22) = 85.4\) pounds.

The volume determined by actual measurement is, of course, more accurate than the calculated value; but measurements after treatment are not always practicable, and the approximate increase in volume can be calculated as shown in this example.

If the specific gravity \(S_a\) and volume \(V_b\) are known for the seasoned wood and the volume after treatment \(V_a\) has been determined from actual measurement, the average specific gravity \(S_g\) of the wood after swelling may be computed, since \(S_a(V_b) = S_g(V_a)\). In this example \(0.5(1.75) = S_g(1.9)\), or \(S_g = 0.46\).

**Total Weight of Wood and Water**

**Example 15 - (Formula 19)**

If the weight when oven-dry is assumed as 30 pounds and the moisture content as 20 percent, find the total weight in pounds per cubic foot.

The total weight \(W_o = W_d(1 + \frac{M}{100})\)

\[= 30 \left(1 + \frac{20}{100}\right) = 36\] pounds per cubic foot.

**Example 16 - (Formulas 20 and 21)**

A round timber has an average diameter of 11 inches and an average depth of sapwood of 1.7 inches. Assume the average specific gravity of the sapwood is 0.48 and that of the heartwood is 0.46, the average moisture content of the sapwood is 20 percent, and the average moisture content of the heartwood is 35 percent. Compute the total weight in pounds per cubic foot. From formula (21)

the percent sapwood \(R_s = 100 \left[\frac{4(1.7)(11 - 1.7)}{(11)^2}\right]\) = 52.3 percent.

Substituting in formula (20) the weight in pounds per cubic foot,

\[W_o = 62.4 \left[(0.48)(0.523)(1.2) + 0.46(1 - 0.523)(1.35)\right] = 37.28\]

Rept. No. 1448
Example 17 - (Formula 20a)

Assume the average diameter and sapwood depth of a round timber is the same as in example 13, but that the timber is green, the average specific gravity of both the sapwood and heartwood is 0.46, the average moisture content of the sapwood is 90 percent and the average moisture content of the heartwood is 38 percent. Compute the weight in pounds per cubic foot.

Substituting in formula (20a) the weight

\[ w = (0.46) (62.4) \left( (0.523) (0.90 - 0.38) + (1.38) \right) = 47.42 \text{ pounds per cubic foot}. \]

Shrinkage and Swelling

Example 18 - (Formula 22)

If the specific gravity \( S_d \) of the oven-dry wood = 0.63 and that of the green wood \( S_g = 0.54 \) compute shrinkage from the green to the oven-dry condition.

Substituting in formula (22)

\[ C = \frac{0.63 - 0.54}{0.63} = 0.143 \text{ of 14.3 percent}. \]

Example 19 - (Formula 25)

With the values of \( S_d \) and \( S_g \) given in example 18 compute the swelling from the oven-dry to the green condition. Substituting in formula (25),

\[ E = \frac{0.63 - 0.54}{0.54} = 0.167 \text{ or 16.7 percent}. \]

Percentage Air Space

Example 20 - (Formula 30)

If the wood has a specific gravity of 0.40 at 12 percent moisture, compute the percentage air space \( P \). The density of the water \( \rho \) is found from figure 9 to be about 1.187 at 12 percent moisture.

Substituting in formula (30),

\[ P = 100 \left[ 1 - 0.4 \left( 0.685 + \frac{0.12}{1.187} \right) \right] = 68.6 \text{ percent}. \]

Rept. No. 1448

-30-
Example 21 - (Formulas 30 and 31)

Assume the wood has a specific gravity of 0.55 when green and the average moisture content is 75 percent. If formula 30 is used $M_k = 30$ and $M_a = (75 - 30) = 45$, $\rho = 1.113$,

$$P = 100 \left[ 1 - 0.55 \left( 0.685 + \frac{0.30}{1.113} + 0.45 \right) \right] = 22.8 \text{ percent.}$$

This is the same as would be shown by formula (31) and substituting $M = 75$ percent. For example using formula (31)

$$P = 100 \left[ 1 - 0.55 \left( 0.685 + \frac{75 - 3.1}{100} \right) \right] = 100 \left[ 1 - 0.55 \left( 0.654 + 0.75 \right) \right]$$

$$= 22.8 \text{ percent.}$$
<table>
<thead>
<tr>
<th>Species</th>
<th>Moisture content</th>
<th>Average specific gravity&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heartwood : Sapwood</td>
<td></td>
</tr>
<tr>
<td>Softwoods:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baldcypress</td>
<td>121 : 171</td>
<td>0.42</td>
</tr>
<tr>
<td>Douglas-fir, coast type</td>
<td>37 : 115</td>
<td>0.45</td>
</tr>
<tr>
<td>Fir, grand</td>
<td>91 : 136</td>
<td>0.37</td>
</tr>
<tr>
<td>Fir, white</td>
<td>98 : 160</td>
<td>0.35</td>
</tr>
<tr>
<td>Hemlock, eastern</td>
<td>97 : 119</td>
<td>0.38</td>
</tr>
<tr>
<td>Hemlock, western</td>
<td>85 : 170</td>
<td>0.38</td>
</tr>
<tr>
<td>Larch, western</td>
<td>54 : 119</td>
<td>0.51</td>
</tr>
<tr>
<td>Pine, lodgepole</td>
<td>41 : 120</td>
<td>0.38</td>
</tr>
<tr>
<td>Pine, ponderosa</td>
<td>240 : 148</td>
<td>0.38</td>
</tr>
<tr>
<td>Pine, eastern white</td>
<td>68</td>
<td>0.34</td>
</tr>
<tr>
<td>Pine, western white</td>
<td>62 : 148</td>
<td>0.36</td>
</tr>
<tr>
<td>Pine, red</td>
<td>32 : 134</td>
<td>0.41</td>
</tr>
<tr>
<td>Pine, southern yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lobolly</td>
<td>33 : 110</td>
<td>0.47</td>
</tr>
<tr>
<td>Longleaf</td>
<td>31 : 106</td>
<td>0.54</td>
</tr>
<tr>
<td>Shortleaf</td>
<td>32 : 122</td>
<td>0.46</td>
</tr>
<tr>
<td>Pine, sugar</td>
<td>98 : 219</td>
<td>0.35</td>
</tr>
<tr>
<td>Redcedar, western</td>
<td>58 : 249</td>
<td>0.31</td>
</tr>
<tr>
<td>Redwood (old-growth)</td>
<td>86 : 210</td>
<td>0.38</td>
</tr>
<tr>
<td>Spruce, Engelmann</td>
<td>51 : 173</td>
<td>0.32</td>
</tr>
<tr>
<td>Spruce, Sitka</td>
<td>41 : 142</td>
<td>0.37</td>
</tr>
<tr>
<td>Hardwoods:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash, green</td>
<td></td>
<td>58 : .53</td>
</tr>
<tr>
<td>Ash, white</td>
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<td>46 : .55</td>
</tr>
<tr>
<td>Beech</td>
<td></td>
<td>55 : .56</td>
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<tr>
<td>Birch, sweet</td>
<td>75 : 70</td>
<td>.60</td>
</tr>
<tr>
<td>Birch, yellow</td>
<td>74 : 72</td>
<td>.55</td>
</tr>
<tr>
<td>Chestnut</td>
<td>120</td>
<td>.40</td>
</tr>
<tr>
<td>Elm, American</td>
<td></td>
<td>95 : .46</td>
</tr>
<tr>
<td>Elm, cedar</td>
<td></td>
<td>66 : .60</td>
</tr>
<tr>
<td>Hickory, water</td>
<td>97 : 62</td>
<td>.61</td>
</tr>
<tr>
<td>Maple, silver</td>
<td>58 : 97</td>
<td>.44</td>
</tr>
<tr>
<td>Maple, sugar</td>
<td>65 : 72</td>
<td>.56</td>
</tr>
<tr>
<td>Oak, black</td>
<td>76 : 75</td>
<td>.56</td>
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<tr>
<td>Oak, northern red</td>
<td>80 : 69</td>
<td>.56</td>
</tr>
<tr>
<td>Oak, southern red</td>
<td>83 : 75</td>
<td>.52</td>
</tr>
<tr>
<td>Oak, swamp red</td>
<td>79 : 66</td>
<td>.61</td>
</tr>
<tr>
<td>Oak, water</td>
<td>81 : 81</td>
<td>.56</td>
</tr>
<tr>
<td>Oak, white</td>
<td>64 : 78</td>
<td>.60</td>
</tr>
<tr>
<td>Oak, willow</td>
<td>82 : 74</td>
<td>.56</td>
</tr>
<tr>
<td>Sweetgum</td>
<td>79 : 137</td>
<td>.44</td>
</tr>
<tr>
<td>Sycamore, American</td>
<td>114 : 130</td>
<td>.46</td>
</tr>
<tr>
<td>Tupelo, black</td>
<td>87 : 115</td>
<td>.46</td>
</tr>
<tr>
<td>Tupelo, water</td>
<td>158</td>
<td>.46</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>83 : 106</td>
<td>.38</td>
</tr>
</tbody>
</table>

<sup>1</sup> Based on weight when oven-dry and volume when green.

<sup>2</sup> Mixed heartwood and sapwood.
Table 2.--Average radial, tangential, and volumetric shrinkage of various commercial species grown in the United States
(Data show average shrinkage from the green to the ovendry condition)

<table>
<thead>
<tr>
<th>Species</th>
<th>Shrinkage from green to ovendry condition (percent of dimensions when green)</th>
<th>Specific gravity based on weight when:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial</td>
<td>Tangential</td>
</tr>
<tr>
<td>Softwoods:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baldcypress</td>
<td>3.8</td>
<td>6.2</td>
</tr>
<tr>
<td>Douglas-fir, coast type</td>
<td>5.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Douglas-fir, intermediate type</td>
<td>4.1</td>
<td>7.6</td>
</tr>
<tr>
<td>Douglas-fir, Rocky Mountain type</td>
<td>3.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Fir, balsam</td>
<td>2.9</td>
<td>6.9</td>
</tr>
<tr>
<td>Fir, commercial white&lt;sup&gt;1&lt;/sup&gt;</td>
<td>3.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Hemlock, eastern</td>
<td>3.0</td>
<td>6.8</td>
</tr>
<tr>
<td>Hemlock, western</td>
<td>4.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Larch, western</td>
<td>4.2</td>
<td>8.1</td>
</tr>
<tr>
<td>Pine, lodgepole</td>
<td>4.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Pine, eastern white</td>
<td>2.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Pine, red</td>
<td>4.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Pine, ponderosa</td>
<td>3.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Pine, southern yellow</td>
<td>4.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Loblolly</td>
<td>5.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Longleaf</td>
<td>4.4</td>
<td>7.7</td>
</tr>
<tr>
<td>Shortleaf</td>
<td>5.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Slash</td>
<td>2.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Pine, sugar</td>
<td>4.1</td>
<td>7.4</td>
</tr>
<tr>
<td>Pine, western white</td>
<td>3.1</td>
<td>4.7</td>
</tr>
<tr>
<td>Redcedar, eastern</td>
<td>2.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Redcedar, western</td>
<td>2.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Redwood, (old-growth)</td>
<td>4.2</td>
<td>7.8</td>
</tr>
<tr>
<td>Spruce, eastern&lt;sup&gt;2&lt;/sup&gt;</td>
<td>3.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Spruce, Engelmann</td>
<td>4.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Spruce, Sitka</td>
<td>3.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Tamarack</td>
<td>2.2</td>
<td>4.9</td>
</tr>
<tr>
<td>White-cedar, northern</td>
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<td></td>
</tr>
<tr>
<td>Hardwoods:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash, commercial white&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aspen, quaking</td>
<td>3.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Basswood, American</td>
<td>6.6</td>
<td>9.3</td>
</tr>
<tr>
<td>Beech</td>
<td>5.1</td>
<td>11.0</td>
</tr>
<tr>
<td>Birch, yellow</td>
<td>7.2</td>
<td>9.2</td>
</tr>
<tr>
<td>Cherry, black</td>
<td>3.7</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Table 2.—Average radial, tangential, and volumetric shrinkage of various commercial species grown in the United States (continued).

<table>
<thead>
<tr>
<th>Species</th>
<th>Shrinkage from green to ovensdry condition (percent of dimensions when green)</th>
<th>Specific gravity based on volume when green = ( S_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwoods:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chestnut</td>
<td>3.4 : 6.7 : 11.6 : 0.40</td>
<td></td>
</tr>
<tr>
<td>Cottonwood, eastern</td>
<td>3.9 : 9.2 : 14.1 : 0.37</td>
<td></td>
</tr>
<tr>
<td>Cottonwood, northern black</td>
<td>3.6 : 8.6 : 12.4 : 0.32</td>
<td></td>
</tr>
<tr>
<td>Elm, American</td>
<td>4.2 : 9.5 : 14.6 : 0.46</td>
<td></td>
</tr>
<tr>
<td>Elm, rock</td>
<td>4.8 : 8.1 : 14.1 : 0.57</td>
<td></td>
</tr>
<tr>
<td>Elm, slippery</td>
<td>4.9 : 8.9 : 13.8 : 0.48</td>
<td></td>
</tr>
<tr>
<td>Hackberry</td>
<td>4.8 : 8.9 : 16.9 : 0.49</td>
<td></td>
</tr>
<tr>
<td>Hickory, pecan (^1)</td>
<td>4.9 : 8.9 : 13.6 : 0.59</td>
<td></td>
</tr>
<tr>
<td>Hickory, true (^2)</td>
<td>7.4 : 11.3 : 17.9 : 0.65</td>
<td></td>
</tr>
<tr>
<td>Honeylocust</td>
<td>4.2 : 6.6 : 10.8 : 0.60</td>
<td></td>
</tr>
<tr>
<td>Locust, black</td>
<td>4.6 : 7.2 : 10.2 : 0.66</td>
<td></td>
</tr>
<tr>
<td>Maple, bigleaf</td>
<td>3.7 : 7.1 : 11.6 : 0.44</td>
<td></td>
</tr>
<tr>
<td>Maple, black</td>
<td>4.8 : 9.2 : 14.0 : 0.52</td>
<td></td>
</tr>
<tr>
<td>Maple, red</td>
<td>4.0 : 8.2 : 13.1 : 0.49</td>
<td></td>
</tr>
<tr>
<td>Maple, silver</td>
<td>3.0 : 7.2 : 12.0 : 0.44</td>
<td></td>
</tr>
<tr>
<td>Maple, sugar</td>
<td>4.9 : 9.5 : 14.9 : 0.56</td>
<td></td>
</tr>
<tr>
<td>Oak, red (^3)</td>
<td>4.4 : 9.3 : 15.8 : 0.56</td>
<td></td>
</tr>
<tr>
<td>Oak, white (^4)</td>
<td>5.2 : 9.8 : 15.9 : 0.59</td>
<td></td>
</tr>
<tr>
<td>Sugarberry</td>
<td>5.0 : 7.3 : 12.7 : 0.47</td>
<td></td>
</tr>
<tr>
<td>Sweetgum</td>
<td>5.2 : 9.9 : 15.0 : 0.44</td>
<td></td>
</tr>
<tr>
<td>Sycamore, American</td>
<td>5.1 : 7.6 : 14.2 : 0.46</td>
<td></td>
</tr>
<tr>
<td>Tupelo, black</td>
<td>4.4 : 7.7 : 13.9 : 0.46</td>
<td></td>
</tr>
<tr>
<td>Tupelo, water</td>
<td>4.2 : 7.6 : 12.5 : 0.46</td>
<td></td>
</tr>
<tr>
<td>Walnut, black</td>
<td>5.5 : 7.8 : 12.8 : 0.51</td>
<td></td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>4.0 : 7.1 : 12.3 : 0.38</td>
<td></td>
</tr>
</tbody>
</table>

Note: To compute the shrinkage due to seasoning from green to any moisture content below fiber-saturation point, multiply figure from table 2 by

\[
(1 - \frac{M}{30})
\]

where \( M \) is the moisture content (percent) to which wood is seasoned.

\(^1\) Average of grand fir and white fir.
\(^2\) Average of black spruce, red spruce, and white spruce.
\(^3\) Average of Biltmore ash, blue ash, green ash, and white ash.
\(^4\) Average of bitternut hickory, nutmeg hickory, water hickory, and pecan.
\(^5\) Average of shellbark hickory, mockernut hickory, pignut hickory, and shagbark hickory.
\(^6\) Average of black oak, laurel oak, pin oak, northern red oak, scarlet oak, southern red oak, water oak, and willow oak.
\(^7\) Average of bur oak, chestnut oak, post oak, swamp chestnut oak, swamp white oak, and white oak.

Rept. No. 1448
Figure 1.--Relation of moisture content based on weight when oven dry and moisture content based on original weight.
Figure 2.—Relation between weight of water in wood, specific gravity, and percentage of moisture.
Figure 3.—Amount of water in wood having any given specific gravity and moisture content.
Figure 4.—Percent of volume filled with water when wood has various amounts of moisture and any given specific gravity.
Figure 5.—Relation of dry bulb temperature, relative humidity, and equilibrium moisture content of wood.
Figure 6.—Relation of moisture content and volumetric shrinkage for woods having different specific gravity values based on weight when oven dry and volume when green.
Figure 7.--Relation of specific gravity and moisture content.
Figure 6.--Relation of original weight, moisture content, and specific gravity based on weight and volume when oven dry.
Figure 9.--Specific gravity of water in cell walls of wood at different percentages of moisture.
Figure 10.—Relation between moisture content, specific gravity, and weight of wood in pounds per cubic foot. (Specific gravity based on weight when oven dry and volume when green.)
Figure 11.—Relation of the maximum moisture content, weight of oven-dry wood, and weight of water in pounds per cubic foot when the wood is completely saturated.