The Dimensional Stability of Wood

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Polyethylene glycol-1000 stabilizes wood by bulking the fibers. It also serves as a chemical seasoning agent, suppresses decay in high concentrations, and has slight effect on physical properties, gluing, or finishing.

Polyethylene glycol of various molecular weights has previously been shown by the author (13) to reduce greatly the shrinkage of thin cross sections of Sitka spruce. After the cross sections were completely filled with a 25 percent aqueous solution of polyethylene glycol of average molecular weight 200, the specimens were slowly air-dried and then oven-dried. They retained their green dimensions, which indicated that the polyethylene glycol had completely replaced the water in the swollen cell walls. Polyethylene glycol-1000 was only slightly less effective in replacing the water as drying progressed.

Cross sections of the wood treated with the high-molecular-weight material tended to be damp only when the equilibrium relative humidity exceeded 90 percent, while those treated with the lower-molecular-weight material tended to remain damp at appreciably lower relative humidities. For this reason, polyethylene glycol-1000 was chosen for further research.

Stabilization of Tree Cross Sections

It appeared from the previous data (13) that polyethylene glycol might serve as a chemical seasoning agent in the same manner as salt and urea (6).

It was tried, therefore, in the seasoning of tree cross sections to determine if it would prevent the formation of the familiar V-shaped radial checks that open in tree cross sections. Twelve tree cross section discs 1.25 inches thick by 10 to 11 inches in diameter where cut from two green southern pine logs. Small brass nails were driven into one face of each disc near the cambium. They were placed on two lines at right angles to each other that passed through the center of the specimens. These served as reference points for measuring the radial shrinkage.

Three discs from each log were soaked in water overnight. The diameters were measured between the nails, and the discs were then placed in the 90 percent relative humidity room. A day or two after the transfer, all of the untreated controls started to develop V-shaped checks, and at the end of 2 weeks they had opened up at the periphery anywhere from 0.9 to 1.5 centimeters. The ratios of width of the checks at the periphery to the radius ranged from 0.075 to 0.105. Only one of the treated specimens showed any open radial checks at the periphery.

Stabilization continued through 16, 48, 96, and 168 hours, soaking, and after the transfer, all of the untreated controls started to develop V-shaped checks, and at the end of 2 weeks they had opened up at the periphery anywhere from 0.9 to 1.5 centimeters. The ratios of width of the checks at the periphery to the radius ranged from 0.075 to 0.105. Only one of the treated specimens showed any open radial checks at the periphery.

Fig. 1.—Cross sections of a southern pine log (11 inches diam., 1.25 inches thick) slowly air dried from the green condition at 90, 65, and then 30% relative humidity. Upper left: water-soaked control; upper right: 8 hours’ soak in 30% aqueous solution of polyethylene glycol-1000; lower left: 16 hours’ soak in the solution; lower right: 48 hours’ soak in the solution.
significant checks, namely, one of those that had a single coat of molten polyethylene glycol. The ratio of the check width to the radius of this single specimen was 0.034.

After 2 weeks in the 65 percent room, all specimens were transferred to the 30 percent relative humidity room. After two more weeks, the checks of the controls had opened up still further. The ratios of width of check to the radius of the discs ranged from 0.142 to 0.192. The check in the disc that had received one surface coat of molten polyethylene glycol had by then opened up to a width-to-radius ratio of 0.124. During this last period, the other specimen that had received one coat of molten polyethylene glycol developed a very slight check with a width-to-radius ratio of 0.016. The two discs that had been soaked in polyethylene glycol for 8 hours developed slight internal radial checks that did not extend to the periphery. All of the other specimens were free from checks.

The polyethylene glycol content of the discs was determined by cutting a small wedge-shaped specimen from the discs, cutting it up into thin shavings, oven-drying and weighing the shavings, impregnating them with water by the vacuum desiccator technique, and boiling them in a large volume of fresh water once a day for several days. They were allowed to stand in the water for the periods between heating. The extracted shavings were then oven-dried and weighed. The polyethylene glycol content was calculated from the loss in weight after a correction was made for the extractive loss of the controls.

The polyethylene glycol content of the various discs together with the radial shrinkage to 30 percent relative humidity, the reduction in shrinkage due to the bulking, and the average check widths divided by the discs radius are given in Table 1. Fig. 1 is a photograph of an untreated and three treated southern pine discs. Fig. 2 gives both the weight of polyethylene glycol—1000 taken up by the tree cross sections, and the reduction in radial shrinkage plotted against the time of soaking and against the number of surface coatings.

The data show that a polyethylene glycol content of 13 percent or more caused a reduction in radial shrinkage of 32 percent or more, and prevented the V-shaped checks from forming. The relationships plotted against the time of soaking are parabolic, and those plotted against the number of surface coatings are linear, as would be expected. An overnight, or longer, soak in a 30 percent solution of polyethylene glycol—1000 or two surface coats a day apart, it appears, will prevent the V-checks in green sapwood discs of southern pine 1 to 1.25 inches thick. As the thickness of the discs increases, the soaking time will have to be increased—probably in proportion to the square of the thickness.

Heartwood will require more soaking time or more coats than will sapwood. Two tree discs of ponderosa pine 1.5 inches thick by 18 inches in diameter were coated with two applications of molten polyethylene glycol a day apart. Fig. 3 shows the dried control (left) and the dried coated disc (right). The two coats were adequate to stabilize the outer sapwood but not the heartwood, as seen by the two narrow honeycomb checks in the heartwood. If the disc had been held under nondrying conditions for a longer time to allow deeper diffusion of the coatings into the heartwood, or if more coats had been applied to the center heartwood than to the outer sapwood, the honeycomb checks might have been prevented.

Rate of Diffusion of Polyethylene Glycol—1000 into Water-Saturated Wood

The previous investigations showed that polyethylene glycols in concentrated aqueous solutions swell wood more than does water alone (13). This makes it possible to determine the diffusion coefficient of polyethylene glycol into water-saturated wood simply by following the rate of swelling in the tangential direction, the direction in which practically all swelling beyond the swelling in water occurs (9). A cross section of Sitka spruce with a thickness in the fiber direction of 0.165 inch was saturated by immersing it in water under a vacuum for 1 hour, followed by soaking overnight under atmospheric pressure. The water-saturated specimen was immersed in molten polyethylene glycol—1000 at 60° C., and the increase in tangential dimension was measured periodically. Fig. 4 is a plot of the tangential swelling beyond that in water plotted against the square root of time. The relationship is linear up to two-thirds of the final swelling. This would be expected for true diffusion when the concentration gradient is parabolic (12, 15). The diffusion coefficient, D, was calculated from the data by means of the Boltzmann modification of Fick’s general diffusion equation (12, 15).

\[
D = \frac{a^2}{16t} \frac{E}{E_a}
\]

(1)

where \(a\) is the thickness of the specimen and \(E\) is the amount of solute that diffuses into the specimen in time \(t\) expressed as a fraction of the final equilibrium amount. The author has previously shown (5) that the fractional swelling, \(E\), can be substituted for the fractional take-up of solute,
Table 1.-EFFECT OF POLYETHYLENE GLYCOL TREATMENTS UPON CHECKING AND SHRINKING OF SOUTHERN PINE TREE CROSS SECTIONS 1.25 INCHES THICK DIFFERENT MOISTURE CONTENT CONDITIONS

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Chemical content</th>
<th>Average radial shrinkage</th>
<th>Radiation in shrinkage</th>
<th>Average ratio of check widths to radii</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td>0</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>Hours of soaking&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td>0</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>0</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.7</td>
<td>1.5</td>
<td>92  none</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>1.5</td>
<td>41  none</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>21.7</td>
<td>1.3</td>
<td>66  none</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>28.5</td>
<td>0.6</td>
<td>73  none</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>39.9</td>
<td>0.4</td>
<td>92  none</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.—DIFFUSION OF POLYETHYLENE GLYCOL-1000 INTO 1/16-INCH-THICK EDGE-GRAIN SITKA SPRUCE VENEER UNDER CROSS SECTIONS 1.25 INCHES THICK DIFFERENT MOISTURE CONTENT CONDITIONS

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>Before polyethylene glycol application</th>
<th>After polyethylene glycol application</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Swelling from oven-dry condition</td>
<td>Amount applied at surface roasting</td>
</tr>
<tr>
<td></td>
<td>Percent</td>
<td>Percent</td>
</tr>
<tr>
<td>30%</td>
<td>4.4</td>
<td>0.86</td>
</tr>
<tr>
<td>65%</td>
<td>9.6</td>
<td>1.40</td>
</tr>
<tr>
<td>80%</td>
<td>9.6</td>
<td>1.40</td>
</tr>
<tr>
<td>90%</td>
<td>9.6</td>
<td>1.40</td>
</tr>
</tbody>
</table>

<sup>a</sup>Dried to 20 percent relative humidity.
<sup>b</sup>Values are the average for six trials.
<sup>c</sup>Calculated for 20 percent relative humidity.
<sup>d</sup>Values are the average for two trials.
<sup>e</sup>Coated with molten polyethylene glycol-1000.

The diffusion coefficient for the polyethylene glycol into the green cross sections of southern pine from the 30 percent solution was also calculated from the data of Fig. 2. A value of 0.5 x 10⁻⁵ cm²/sec. was obtained. This slightly larger value can be accounted for on the basis that some capillary absorption took place, since the wood, although green, was not completely saturated with water.

**Diffusion into Wood at Different Moisture Contents**

A means of dimensionally stabilizing wood in service has long been sought. Therefore, it seemed worth while to determine how well a surface application of polyethylene glycol penetrates the cell-wall structure of wood at different moisture contents. Twelve specimens of edge-grain Sitka spruce veneer 1/16 inch thick by 5 inches in the radial direction and 3 inches longitudinally were oven-dried, weighed, and their radial dimension measured. Three specimens were placed in each of the following relative humidity rooms: 30, 65, 80, and 90 percent; they were allowed to come to equilibrium moisture content, after which the weight increase and radial swelling were determined. A coat of molten polyethylene glycol was applied to both faces of two sheets out of each set of three sheets of the veneer. After the sheets remained in the same relative humidity room for five more weeks, the radial dimension of the veneer was again measured. No change occurred for the controls or the coated specimens in the 30 percent relative humidity room.

The coated specimens in the higher relative humidity rooms all showed additional swelling that increased with an increase in the relative humidity. The data are given in Table 2. They show that polyethylene glycol must have diffused into the cell walls, and that the amount that entered exceeded the amount of water displaced. At 90 percent relative humidity an amount of polyethylene glycol equivalent to at least 2.8 percent of the weight of the wood must have diffused into the cell-wall structure. Even at this high relative humidity.
Results of the impregnation of the veneer and plywood are shown in Table 1. The amounts of polyethylene glycol absorbed by the veneer are given in parts per hundred of the dry weight. The values for the plywood samples are also shown. The increase in weight of the plywood is due to the swelling of the green veneer material and the absorption of water or polyethylene glycol by the layers of the plywood. The increase in weight is attributed to the swelling of the green veneer material and the absorption of water or polyethylene glycol by the layers of the plywood.
Yellow Birch Veneer with Polyethylene Glycol-1000 Upon the Dimensional Stability and on the Toughness

Table 3 — Effect of Impregnating 1/16 Inch Thick Edge Grain Sitka Spruce Veneer with Polyethylene Glycol-1000 Upon the Relative Abrasion Resistance of the Veneer and the Relative Toughness of the Veneer Specimens

<table>
<thead>
<tr>
<th>Chemical content</th>
<th>Reduction in weight/shrinkage</th>
<th>Relative toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>11.3</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>20.6</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>30.8</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>40.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Average for four specimens 5 inches radially by 3 inches longitudinally.
*From dry-to-equilibrium with 65 percent relative humidity.
*Average for 10 specimens 0.35 inch radially by 3 inches longitudinally cut from each of the four original specimens.

The practical elimination of decay occurred when the reduction in swelling was 50 percent and more. Under these conditions only half of the normal amount of water can enter the fiber. This evidently is insufficient to support decay.

Properties of Green Wood Relative to Wood at 12 Percent Moisture Content

In no cases is the loss in strength due to impregnation with polyethylene glycol significantly greater than would be expected from the extent of bulking of the fibers, which is indicated by the decrease in the ratio of the specific gravities.

Decay Resistance

A flat-sawn Sitka spruce board 5 inches wide by 0.5 inch thick was cut into a series of specimens 0.5 inch in the fiber direction for decay-resistance tests. The specimens were impregnated by the vacuum desiccator technique with 0, 5, 10, 20, and 40 percent solutions of polyethylene glycol–1000 dissolved in water, resulting in polyethylene glycol contents of the wood ranging from 8.6 to 63.7 percent. The specimens were air-dried to equilibrium with 30 percent relative humidity and then subjected to the standard block culture test (1) for 3 months after inoculation with *Lenzites trabea*.

Because washing to remove the fungus and decay products also extracted polyethylene glycol from the specimens, the weight-loss technique for determining the amount of decay could not be used. The extent of decay was thus judged qualitatively by the ease of penetration of a knife blade into the structure. All specimens that contained at least 17.6 percent of polyethylene glycol were perfectly sound. Specimens that contained only 8.6 percent of polyethylene showed some evidence of decay, while the controls were badly decayed. Culture tests showed that polyethylene glycol–1000 is nontoxic.

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Gluing Tests

A number of the potential applications of the polyethylene-glycol-treated wood will depend upon its gluability. To determine this factor, two sheets of rotary-cut yellow birch veneer 1/16, inch thick were each cut into 4 strips 5 inches wide in the tangential direction and parallel to a split edge in order to get the grain as straight as possible. The strips were cut into twelve 3-inch lengths, which gave a total of 96 3-inch by 5-inch pieces of veneer. The experiment involved 3 levels of treatment and an untreated control, 6 different glues, and 2 specimen replications, each of which consisted of 2 strips glued together to form lap joints. Pieces cut from one sheet were then subjected to the standard block culture test (1) for 3 months after inoculation with *Lenzites trabea*.

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vinyl emulsion, cold-setting resorcinal, and hot animal glues gave somewhat decreasing tensile strengths and decreasing or erratic percentages of wood failure with increasing polyethylene glycol contents.

Confirmatory tests were made on a duplicate set of samples. In the second series, both the polyvinyl emulsion and the resorcinal glues still showed a tendency to decrease in tensile strength with an increase in polyethylene glycol content, but they did give higher wood failure values. The hot animal glue gave good tensile values that did not decrease with increasing polyethylene glycol content, and more consistently high wood failure values. The lowest tensile strength value obtained in the second series was 450 psi with a wood failure of 12 percent for the cold-setting resorcinal resin and the highest polyethylene glycol content. The data thus indicated that quite good glue joints can be obtained for wood containing as much as 33 percent of polyethylene glycol. Casein, cold-setting urea, and hot-setting phenolic resin gave the best results.

The marked suitability of hot-setting phenolic resin for gluing the treated veneer was noted above in the discussion of the face-checking tests. The cycling of the glued-up panels between 90 and 30 percent relative humidity set up a very severe stress at the glue line. None of the panels showed any sign of delaminating under this rigorous treatment.

Finishing Tests

Standard ponderosa pine paint-test panels 2/4 inches wide by 6 inch thick were each cut into two equal 5.5-inch lengths. One half of each of the end-matched specimens was impregnated with polyethylene glycol solution and the other half with water by the vacuum desiccator technique. Three concentrations were used, namely, 10, 20, and 40 percent; these gave polyethylene glycol contents of 10 to 13 percent, 18 to 24 percent, and 36 to 50 percent on the basis of the dry weight of the wood. This variability was due to the nonuniformity of the wood. The specimens were all dried at 65 percent and then 30 percent relative humidity.

Seven different finishes were applied to the specimens. These were a floor sealer, shellac, phenolic resin spar varnish, alkyd resin clear varnish, a clear lacquer, natural exterior finish (Forest Products Laboratory No. 497), and an exterior white paint. Two coats of each finish were applied to three specimens that contained the three different amounts of polyethylene glycol and their corresponding controls. The panels were inspected 24 hours after application of the first coat. In all cases the specimens that contained polyethylene glycol were much more tacky than the controls which indicates that drying was retarded by the chemical. The panels were hence allowed to dry for a few more days before application of the second coat. Three days after the second coat was applied, all of the specimens were impregnated with polyethylene glycol were somewhat tacky, especially the ones containing the largest amount.

Two months later the panels were carefully examined. All of the impregnated panels with clear finishes were lighter in color than the unimpregnated controls. This was especially noticeable with the varnishes. The panels that contained the lower two levels of polyethylene glycol were dry to the touch like the unimpregnated controls. The specimens containing the largest amount of polyethylene glycol that were coated with floor sealer and shellac were also dry. All of the others had a slight tendency to bond to one’s finger when pressed firmly on the surface.

The slow drying of the finishes can be partly attributed to the fact that the finishes were applied during the humid summer months. Three coats of a polyurethane varnish and three coats of outside white paint were applied to redwood specimens for leaching tests described later. The finishes were applied at 30 percent relative humidity. Three days after the final coats, the varnish was applied on the polyethylene-glycol-impregnated specimens, but the outside white paint was still slightly tacky. Excepts for the retarded rate of drying, it appears that polyethylene-glycol-impregnated wood can be satisfactorily finished.

Leaching Tests

It is well known that all wood finishes are somewhat permeable to water (5). There was a question, however, whether they would be permeable to polyethylene glycol with a molecular weight of 1000. Experiments were made to determine if varnish or paint finishes acted as semipermeable membranes and tended to retain polyethylene glycol within the wood under leaching conditions, and also to determine if the osmotic action tended to blister or loosen the films from the wood.

A 0.75-inch-thick, edge-grain redwood board 3.75 inches wide was cut into 3-inch-long specimens in the fiber direction. All corners and edges were rounded by sanding. Eight specimens were impregnated with 30 percent solution of polyethylene glycol-1000 to give an average chemical content of 39 percent. These specimens together with an untreated control were conditioned to 30 percent relative humidity. Three of the impregnated specimens were given three coats of a polyurethane varnish and three were given three coats of a commercial white house paint. When the finishes were dry, the specimens were weighed and measured. These six specimens together with the two impregnated but uncoated specimens and the unimpregnated uncoated specimen were immersed in running water for two weeks. The weight increase of the unimpregnated nonsurface coated specimen was 57 percent. The impregnated but non-surface-coated specimens increased on the average.

Table 5. - RATIO OF THE PHYSICAL AND STRENGTH PROPERTIES OF SITKA SPRUCE STICKS (0.5 BY 5 BY 13 INCHES) IMPELLATED WITH POLYETHYLENE GLYCOL-1000 TO THE VALUES FOR END-MATCHED UNIMPELLATED CONTROLS (THIRD-POINT TANGENTIAL LOADING)

<table>
<thead>
<tr>
<th>Chemical content</th>
<th>Specific gravity</th>
<th>Modulus of elasticity</th>
<th>Fiber stress at proportional limit</th>
<th>Modulus of rupture</th>
<th>Work to proportional limit</th>
<th>Work to maximum load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td>0.94</td>
<td>0.79</td>
<td>90</td>
<td>0.97</td>
<td>0.35</td>
<td>1.18</td>
</tr>
<tr>
<td>20.0</td>
<td>0.80</td>
<td>0.75</td>
<td>85</td>
<td>0.62</td>
<td>0.27</td>
<td>0.81</td>
</tr>
<tr>
<td>45.5</td>
<td>0.84</td>
<td>0.70</td>
<td>75</td>
<td>0.48</td>
<td>0.19</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 6. - EFFECT OF POLYETHYLENE GLYCOL-1000 ON THE GLUING OF YELLOW BIRCH VENEER

<table>
<thead>
<tr>
<th>Glue</th>
<th>Tensile strength of glue joint for chemical content of 0 percent</th>
<th>Tensile strength of glue joint for chemical content of 15 percent</th>
<th>Wood failure at glue joint for chemical content of 0 percent</th>
<th>Wood failure at glue joint for chemical content of 15 percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Psi</td>
<td>Psi</td>
<td>Psi</td>
<td>Psi</td>
</tr>
<tr>
<td>Casin</td>
<td>712</td>
<td>726</td>
<td>722</td>
<td>710</td>
</tr>
<tr>
<td>Polyvinyl</td>
<td>575</td>
<td>584</td>
<td>584</td>
<td>570</td>
</tr>
<tr>
<td>Cold-setting urea</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>490</td>
</tr>
<tr>
<td>Cold-setting resorcinal</td>
<td>572</td>
<td>552</td>
<td>552</td>
<td>540</td>
</tr>
<tr>
<td>Hot-setting phenolic</td>
<td>500</td>
<td>515</td>
<td>525</td>
<td>510</td>
</tr>
<tr>
<td>Hot animal glue</td>
<td>575</td>
<td>575</td>
<td>575</td>
<td>565</td>
</tr>
</tbody>
</table>

*Experiments 1 inch wide by 1 inch overlap.
*Each value is the average of 6 determinations.
age 53 percent in weight. The average increase in weight of the varnished specimens was only 2.6 percent, and of the paint-coated specimens, 3.8 percent. This small weight increase merely raised the average moisture content of the specimens from 7 percent to 10 to 11 percent. Under these conditions, polyethylene glycol was not leached out to any measurable degree.

The specimens were oven-dried, weighed, and measured. The impregnated specimens that were not surface-coated had lost a little over half of their polyethylene glycol during leaching. The paint-coated specimens blistered during the drying, but the varnish-coated specimens did not. It thus appears that, in spite of the fact that polyethylene glycol can be readily leached from wood, a good surface coating retains practically all of it in the wood.

Conclusions
Polyethylene glycol-1000 is shown to be a good seasoning and dimension-stabilizing agent for wood. Although an amount of chemical equivalent to about 30 percent of the dry weight of the wood is required to give high degrees of dimensional stabilization, less is needed to cut down face checking that results from seasoning and occurs due to humidity changes in service.

Although the chemical can be leached from wood, surface coatings do an excellent job of keeping them in the wood.

The toughness of wood is not reduced by the treatment as is the case for most other dimension-stabilizing agents. Static-bending and abrasion-resistance properties are reduced only to the extent that would be expected from the bulking of the fibers.

The treated wood has good decay resistance and can be readily glued and finished, but the rate of drying of finishes is greatly retarded.

Literature Cited