DURABILITY OF WATER-RESISTANT WOODWORKING GLUES

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The increasing use of glues in the fabrication of items of wood and wood products, the increasing variety of the items, and the development of new glues and important modifications of old ones, all serve to increase the problem of selecting a satisfactory glue for a particular purpose. Selecting the proper adhesive requires, among other things, a knowledge of the conditions to which the glued item will be exposed in normal service, and a knowledge of the characteristics of the different glues available. Since essentially all of the woodworking glues now in common use are capable of producing joints that are initially strong when dry, the choice of a glue centers largely on the durability under conditions other than those within the range of human comfort, and on the practical consideration of cost and adaptability to production procedures.

The range of conditions under which different glued items are expected to serve vary widely. Much of the furniture in the north temperate zone, for example, is seldom exposed to temperatures much beyond the human comfort zone nor to atmospheres damp enough to permit mold growth. Toward the other extreme, glued laminated timbers are being used in the construction of bridges, where they will be expected to retain a high percentage of their strength even though installed in damp locations, repeatedly wetted and dried, and exposed to wide variations in temperature. Some glued wood products used in boat construction may be continuously immersed, while other members, like the ribs, may be continuously damp in some locations, warm and dry in others, and hot in still others. Glued wood parts in aircraft may be repeatedly wetted and dried, continuously damp, or subjected to extremely high temperatures, depending on the location of use. Temperatures of about 215° F. have been recorded immediately beneath the dark-colored plywood wing skins of aircraft during
Arizona summers. Some glued wood elements used in house construction may be fully exposed to the weather, others to an occasional accidental wetting and prolonged dampness, while others may remain dry but reach temperatures somewhat above 150° F. during warm summer days.

Requirements as to permanence also vary widely. In some cases, the glue joints need hold only until the item is fully assembled, while other uses, as in glued structural members in housing, the glue joints will be expected to retain approximately full strength and quality for an indefinite number of years.

In general, three methods of measuring the durability of glued joints have been employed:

1. Laboratory exposure tests of plywood
2. Weathering tests of plywood panels
3. Exposure tests of laminated beams

Each of these methods will be considered in turn in sections of this report. For each method of testing, an evaluation of the glues for which data are available, will be presented.

forest products laboratory exposure tests of plywood

Exposure tests of plywood under controlled conditions in the Laboratory have supplied a major part of the available data on the durability of glues. To date these tests have given information on the resistance of various glues in plywood joints exposed to severe moisture conditions for periods up to 10 years and to extreme temperature conditions for periods up to 3 years.

Data presented in this section were originally compiled under the direction of H. D. Bruce. They are the result of the work of many investigators, but particularly Don Brouse, W. Z. Olson, and R. F. Blomquist.

Test Procedure

Most of the Laboratory data are based on tests of standard plywood shear specimens that were prepared from 1/16-inch yellow birch veneer and glued at 12 percent moisture content. Manufacturers' recommendations governed the gluing conditions used. Control samples were tested both wet and dry after a 1-week conditioning period, and the remaining specimens were subjected to various conditions of exposure. At regular intervals, samples were removed and shear strength was determined. Specimens were generally tested in the condition at which they were removed. Specimens subjected to cyclic exposures were usually tested after the dry part of the cycle.

Exposure Conditions

No single exposure test can be used for an accurate evaluation of the durability of glued joints under varied service conditions. By means of well-selected sets of conditions to which each glue has been exposed, however, the individual factors that lead to the deterioration of glued joints can be isolated, and the relative resistance of particular glues to these conditions can be compared. The properties of glued joints determined in this way include resistance to water, to molds and other micro-organisms, to high and low temperatures, and include ability to withstand mechanical stresses caused by restraint of swelling and shrinking due to the cross-ply construction of the specimens. From a knowledge of these properties, gained as a result of extensive laboratory tests, glues can be rated with regard to their effectiveness under known conditions of service.

The exposure conditions used in these laboratory tests, together with a statement of the significance of each, follow:

Continuous soaking in water at room temperature. --This is primarily a test of water resistance, although bacterial action may be involved, particularly with protein glues.

Continuous exposure to 97 percent relative humidity and 80° F. --In this test, resistance to a combination of mold and other micro-organisms and ability to withstand the effects of moisture content approaching fiber saturation are measured.

Soaking-drying cycle. --This test consists of repeated cycles of alternate soaking in water at room temperature for 2 days and drying at 80° F. and
30 percent relative humidity for 12 days. Resistance to mechanical stresses, to water, and possibly to biological deterioration is necessary for maintenance of strength under this exposure cycle.

High and low relative humidity cycle. --In this test, a period of 2 weeks at 80° F. and 97 percent relative humidity is followed by a 2-week period at 80° F. and 30 percent relative humidity in a repeating cycle. Mechanical strength, resistance to molds and other micro-organisms, and ability to withstand the effects of moisture content approaching fiber saturation are measured.

Continuous exposure at 80° F. and 65 percent relative humidity. --The effect of aging of the glued joint under mild conditions is measured.

Continuous exposure at 158° F. and 20 percent relative humidity. --The effect of high temperature at low moisture content is indicated.

Continuous exposure at 158° F. and 60 percent relative humidity. --In this test, the combined effect of high temperature and moderate moisture content is indicated.

Room-temperature--high-temperature cycle. --This cycle, consisting of repeated alternate exposures for 16 hours at 80° F. and 65 percent relative humidity and 8 hours at 158° F. and 20 percent relative humidity, measures the combined effect of high temperature and moderate to low moisture content, together with resistance to mild swelling and shrinking stresses.

Room-temperature--low-temperature cycle. --This repeated cycle of alternate exposures for 16 hours at 80° F. and 65 percent relative humidity and 8 hours at -20° F. measures the resistance of moisture-containing glued joints to extremely low temperatures. Early results obtained in this test were based upon a low temperature of -67° F. over dry ice.

Continuous exposure at 200° F. and 20 percent relative humidity. --This is an accelerated test method that measures the comparative resistance of glue and wood to high temperature.

Results of Laboratory Exposure Tests on Eight Types of Glue

The results of exposure to these conditions for various periods of time on the dry shear strength of yellow birch plywood specimens glued with
eight types of glue are shown in figures 1 to 10. Shear-test results for
room-temperature-setting urea resin, casein, intermediate-temperature
phenol resin (alkaline type), hot-press urea resin, fortified urea resin,
resorcinol resin, hot-press phenol resin, and melamine resin glues are
plotted separately. The curves shown in each graph represent average
joint strength after exposure as a percentage of original dry shear strength.
The vertical bars indicate average percentages of wood failure. Differences
between glues of the same type are not revealed by the curves in
figures 1 to 10. Some variations in durability within particular types of
glue are discussed later in this section.

In addition to the eight types of glue for which exposure data are discussed
in this section, animal and vegetable (starch) glues have been tested in
plywood joints under relatively mild exposure conditions. In exposures
involving continuous 30 percent relative humidity and cycles of 60 and 30
percent relative humidity, no deterioration was evident throughout more
than 3 years of exposure. In a cycle consisting of alternating 80 percent
and 30 percent relative humidity, however, glues of both types decreased
rapidly in strength, and joints failed completely in about 1-1/2 years.
Similar failures occurred in 8 months when plywood specimens were ex­
posed to a 90 percent - 30 percent relative humidity cycle, in 3-1/2
months when exposed to a 97 percent - 30 percent relative humidity cycle,
and during the first cycle when subjected to alternate soaking and drying.

After continuous soaking in water at room temperature (fig. 1), joints
glued with casein glues dropped below 40 percent of their original dry
strength within 2 months, and failed completely after 1-1/2 years. Wood-
failure percentages estimated from casein glue joints were low. Joints
glued with room-temperature-setting and hot-press urea resins and hot-
press phenol resins showed high wood-failure values in shear tests
throughout 4-1/2 to 6 years of exposure, which indicates that declining
wood strength rather than declining strength of the glue is shown by the
shear-strength curve. Test data for fortified hot-press urea resin,
resorcinol, melamine, and intermediate-temperature phenol glues are
available for at least 30 months of exposure, during which period high
strengths and high percentages of wood failure were maintained.

Other Laboratory tests—of urea-resin-glued plywood and laminated joints
made from a number of different species and immersed in water and in 4
percent salt solution at room temperature and at 110°F. have shown that,

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4 Blomquist, R. F. Summary of Available Data on the Stability of Glue
Joints in Laminated Oak Keels in Fresh and Sea Water. Forest
Products Laboratory Unnumbered Report. 1943.
under these conditions, deterioration of the glue bond occurs, particularly with certain woods such as white oak and Douglas-fir. In yellow birch, similar deterioration occurred when specimens were soaked in salt water. Apparently some chemical reaction, possibly the liberation of acids, when certain woods are soaked in water or in salt solution is the cause of the rapid decrease in strength. Intermediate-temperature phenol, melamine, and resorcinol resins maintained the full strength of the wood in joints subjected to prolonged soaking in salt water.

Under continuous exposure to 97 percent relative humidity and 80° F. (fig. 2), casein glue dropped below 40 percent of its original dry strength in 4 months, and failed completely in 2-1/2 years. Hot-press and room-temperature-setting urea resins fell to approximately the 60 percent level in 1 year, but continued to show some measurable strength for several years. The hot-press ureas still retained a small percentage of their original strength after 7 years, although the cold-setting urea resin (all of which met the Army-Navy Aeronautical Specification AN-G-8 of April 25, 1942), failed completely in 5 years. The wood undoubtedly deteriorated under this severe exposure condition and contributed to the reduction in joint strength. Decreased percentages of wood failure indicate, however, that the glue bonds also broke down. The strength of fortified urea-resin glue joints was not much better than that of the other urea resins after 42 months of exposure, although wood-failure percentages remained high. After 7 years of exposure, the hot-press phenol glue joints retained better than 40 percent of their original strength, and the high percentages of wood failure indicate that joint strength was limited by the declining strength of the wood. The intermediate-temperature phenol, resorcinol, and hot-press melamine glues were comparable to the hot-press phenol-resin glues.

After exposure to the soaking-drying cycle (fig. 3), casein glues failed rapidly. They dropped below 40 percent of their original dry strength within 4 months. The room-temperature-setting urea glues dropped below 60 percent of their original strength within 18 months, and continued to lose strength throughout the 4-year exposure period. Decreasing strength was accompanied by very low wood-failure values. The hot-press and fortified hot-press urea resins maintained 60 percent of their original joint strength for 3 years, but were not quite so durable as the hot-press phenol resins. The hot-press phenol resins maintained a high level of wood failure throughout the 6-year exposure period, which indicates high durability of the glue. The intermediate-temperature phenol, resorcinol, and hot-press melamine glues retained high strength and wood-failure values, and appear to be comparable to hot-press phenols in durability.
In the high and low relative humidity cycle (fig. 4), the hot-press and the intermediate-temperature phenol, resorcinol, and hot-press melamine resins retained approximately 80 percent of their original strength after 30 months of exposure. The hot-press phenols, for which data are available for a longer period, remained at this level even after 6 years. These glues maintained high percentages of wood failure under this exposure cycle. Casein glue failed rapidly, and dropped below 60 percent of the original joint strength within 1 year. Room-temperature-setting urea-resin glue fell to approximately the 60 percent level within 1 year, and continued to decline rapidly in strength. Recreasing percentages of wood failure indicated deterioration of the glue bond. The hot-press urea resins showed somewhat better resistance to alternating high and low relative humidity conditions, but strength values were very low, and tested specimens showed no wood failure after 4 years of exposure. The fortified hot-press ureas retained higher strength than the hot-press ureas, but some of them showed a gradual decline in wood-failure values over a 30-month period.

When continuously maintained at 80° F. and 65 percent relative humidity for a period of 3 years (fig. 5), the room-temperature-setting urea resins were the only glues tested that showed a trend toward decreasing average joint strength. This weakening was confirmed by a regular drop in percentage of wood failure. At the end of 3 years of exposure, the average joint strength of glues of this type conforming to Army-Navy Aeronautical Specification AN-G-8 (April 25, 1942) had decreased to 72 percent of the original values, but considerable differences existed between individual glues. All other types of glue maintained high levels of strength throughout 3 years of exposure to this mild condition.

At 158° F. and 20 percent relative humidity (fig. 6), room-temperature-setting and hot-press urea resins showed a rapid decline in joint strength and percentage of wood failure, and fell below 60 percent of their original strength within 6 months and 12 months, respectively. The remaining thermosetting resins and casein retained higher joint strengths over the exposure period of 30 months for which data are available, although some fortified urea-resin glues showed a tendency to decrease in strength and wood failure, and casein glues had dropped to approximately the 55 percent level at the end of 30 months. Joints glued with the phenol, resorcinol, and melamine resins declined somewhat in strength under this exposure, but retained high percentages of wood failure, which indicates deterioration of the wood rather than of the glue.
The higher moisture content prevailing under continuous exposure at 158° F. and 60 percent relative humidity (fig. 7) caused a more rapid breakdown of room-temperature-setting urea-resin glue joints. Within 2 months of exposure, room-temperature-setting urea-resin glue joints fell below 50 percent of their original joint strength, and only a few specimens retained measurable joint strength at the end of 9 months. The only hot-press urea resin in these tests deteriorated less rapidly, but it had lost practically all strength after 18 months. Results obtained in up to 18 months of exposure show considerable decrease in the strength and percentage of wood failure of joints glued with some fortified hot-press ureas. Variations in glues of this general type are discussed later in this section. Joints glued with alkaline intermediate-temperature phenol, hot-press melamine, and resorcinol resins showed high average percentages of wood failure after various periods of exposure up to 18 months. Their strength appears to be limited by the decreasing strength of the wood under this high-temperature exposure. Although they were not generally characterized by high wood-failure values, joints glued with casein and hot-press phenol resin both retained high strength under this exposure.

Exposure to the room temperature - high temperature cycle (fig. 8) caused room-temperature-setting urea-resin glued joints to decrease considerably in strength. Within 6 months, strength values for the room-temperature-setting urea-resin glues dropped below 60 percent of original strength and were accompanied by a noticeable decline in wood-failure values. Joint strengths obtained with some fortified hot-press ureas and with hot-press urea resin decreased only moderately, but they were accompanied by a dropping off in wood-failure percentages over exposure periods ranging from 18 to 36 months. Casein glue joints decreased in strength at about the same rate as hot-press urea, but showed no evident trend toward reduced wood-failure values. Hot-press and intermediate-temperature phenol, resorcinol, and melamine glues retained high wood-failure values throughout exposure periods of 18 to 36 months, and joint strength appeared to be limited by the strength of the wood. Gradual weakening of wood takes place under these exposure conditions.

The room temperature - low temperature cycle (fig. 9) showed little difference among the glues tested during 1 to 3 years of exposure. All retained moderately high to high joint-strength values, although with the room-temperature-setting urea, wood-failure percentages were negligible after 3 years and a gradual decline in strength was evident under this condition of exposure.
Continuous exposure at 200° F. and 20 percent relative humidity (fig. 10) accelerated the rate of deterioration of the room-temperature-setting, hot-press, and some fortified hot-press urea resins shown by the exposures at 158° F. Room-temperature-setting urea resins failed completely in 6 months, and hot-press urea resin in 1 year. The fortified urea resins retained some strength after 18 months, but wood-failure values were negligible after this period of exposure. With the remaining thermosetting resins and casein included in these tests, the decreasing strength curves over a 30-month period are similar and appear to reflect chiefly the weakening effect on wood of prolonged periods of exposure to high temperature.

Durability Variations within Particular Types of Glue

The results discussed in the preceding section are based on average data collected for each type of glue. Within any glue type, some glues are superior to others of the same type, and there are also modifications of certain types of glue that cannot be included readily in a generalized summary. It is particularly important to consider such differences in the room-temperature-setting and hot-press urea resins, casein, intermediate-temperature phenol, and fortified urea-resin types.

Room-temperature-setting urea resin. --The results shown in figures 1 to 10 are based only on glues of this type that conformed to Army-Navy Specification AN-G-8 (April 25, 1942). In figure 11, relative joint-strength values after exposure for periods up to 30 months to continuous 80° F. and 65 percent relative humidity, repeated cycles of 97 percent and 30 percent relative humidity at 80° F., continuous 158° F. and 60 percent relative humidity, and to the room temperature-high temperature cycle, are shown for the most durable and the least durable room-temperature-setting urea-resin glues that have been tested at the Forest Products Laboratory, including glues that failed to conform to Specification AN-G-8. Average results are also shown for glues that met the requirements of Specification AN-G-8. Although considerable differences are shown between the best and the poorest glues of this type, the trend toward rapid decline in strength under high humidity and high temperature conditions is shown by all the room-temperature-setting urea resins, and the curves based upon average results obtained with AN-G-8 glues appear to represent the better glues of this type reasonably well.

Hot-press urea resin. --For many purposes, urea-resin glues are extended with flour to reduce glue-line costs. The durability of glues
modified in this way cannot be estimated from the results shown in figures 1 to 10, which are based upon unextended glues. Birch plywood specimens glued with an unextended hot-press urea resin and with the same resin containing various amounts of rye-flour extender up to 200 percent (based on the dry weight of the resin) were therefore placed in 4 of the regular laboratory plywood exposure tests. The results shown in figure 12 cover a 7-year period of exposure. Actual shear strengths are plotted in this figure. Figure 12A shows the effect of soaking on the wet strength of the unextended and flour-extended resins. The original wet strength of the glue extended 200 percent was approximately one-half that of the unextended resin, and a nearly constant difference in strength was maintained throughout the entire period of exposure as the strength of both glues gradually decreased. With 100 percent flour extension, intermediate strength values were obtained.

When specimens were subjected to alternate soaking and drying, shear tests were made following the dry portion of the cycle (fig. 12B). The effect of extension on original strength was relatively slight. The unextended and the 100-percent-extended urea resins decreased in strength at about the same rate as when they were continuously soaked. The specimens glued with resin containing 200 percent extender decreased somewhat more rapidly and failed after 6 years of exposure.

Rapid deterioration of flour-extended urea resins occurred as a result of attack by molds when specimens were exposed continuously to 97 percent relative humidity (fig. 12C) and to the high and low relative humidity cycle (fig. 12D). Under continuous exposure to high humidity, the joints glued with 200-percent-extended resin failed completely in 2 months, and those with 100 percent extender failed in 18 months. The 50-percent-extended resin showed only slightly higher strength than the resin extended 100 percent, although complete failure did not occur until 4 years of exposure. The unextended urea resin declined gradually in strength and wood failure, and failed completely after 7 years of continuous exposure to high humidity. In the high and low humidity cycle, joints glued with 200-percent-extended resin failed completely in 6 months, and those with 100 percent extender failed in 2 years. With 50 percent extender, durability was again only slightly better. The unextended urea resin failed gradually under these conditions, similarly to its performance under continuous high-humidity exposure.

Casein. --Continuous exposure at 80° F. and 97 percent relative humidity was shown in figure 2 to result in the rapid breakdown of casein-glued joints. Experiments were therefore started to show the effect of adding
preservatives to casein glue to increase its durability under exposure to high humidity conditions favorable to the growth of micro-organisms. Two preservatives, beta naphthol and creosote, were added to a commercial casein glue and to Forest Products Laboratory formula 4B casein glue in exposure tests of birch plywood. The addition of 10 percent beta naphthol or 20 percent of creosote to the glue, based on the weight of the dry glue powder, resulted in clearly increased durability when specimens were exposed continuously to 95 to 99 percent relative humidity and 80° F. Under these conditions of exposure, considerable decay had developed in the wood at the end of 20 months. Tests made after longer exposure periods measured decreasing wood strength rather than the quality of the glue joints.

More recently developed preservatives, such as chlorinated phenols and their sodium salts, show a similar effectiveness in preventing organic deterioration of casein glues under high-humidity exposures that are especially favorable for the growth of molds and other micro-organisms. The improvement in mold resistance obtained with such preservatives added to two commercial casein glues is shown in figure 13. Retention of more than 60 percent of original dry strength and relatively high percentages of wood failure is shown throughout an 18-month period of continuous exposure at 80° F. and 97 percent relative humidity by the glues containing 5 percent pentachlorophenol (fig. 13A). The same commercial casein glues without preservative, however, characteristically decreased rapidly in strength under the same condition of exposure. Evidence that the effectiveness of casein glue to which a preservative has been added is not appreciably changed at normal or elevated temperatures is given in figure 13 (B and C), which is based on exposure of the same commercial glues at 80° F. and 91 percent relative humidity and at 158° F. and 60 percent relative humidity for 18 months.

Short-term tests of birch plywood glued with casein glue containing various preservatives and subjected to extreme conditions favorable to mold development showed improved retention of joint strength compared to plywood glued with casein glue without preservative. In these accelerated tests, sapwood shear-test specimens were soaked in water containing mold spores and then stored in a moisture-saturated atmosphere at 72° to 80° F. before they were tested. Results are presented in table 1. Under these conditions, joints glued with a commercial casein glue without

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preservative had failed almost completely in 1 week, whereas the glues containing 5 percent of preservative retained considerable strength, in some cases with high percentages of wood failure, after 16 weeks of exposure.

Although evidence obtained from 48-hour soaking tests indicates that the resistance of casein glues to short periods of soaking is not consistently improved by the addition of preservatives, disinfected casein-glued specimens have been found to resist continuous soaking in water better than specimens that were subject to bacterial attack when similarly exposed. The possibility is indicated that some improvement may result from using preservatives that are effective against bacteria. Results of prolonged periods of soaking or soaking-drying cycles are not available for casein glues containing a preservative.

Intermediate-temperature phenol resin. --Although intermediate-temperature phenol resins are available in two distinct types, alkaline catalyzed and acid catalyzed, the durability values shown in figures 1 to 10 for intermediate-temperature phenols are based upon results obtained only from alkaline-catalyzed glues. In some of the earlier tests, the glued joints were cured for 16 hours at 140° F. Later work has shown that these conditions are not sufficient for complete cure of many glues of the intermediate-temperature phenol type, and in later tests curing periods as long as 8 hours at 220° F. were used to assure complete cure of the resin.

The average values shown in figures 1 to 10 indicate that the alkaline-catalyzed intermediate-temperature phenol resins, when properly cured, are comparable in durability to the hot-press phenols. Results obtained with acid-catalyzed intermediate-temperature phenols were considerably different. In figure 14, a typical acid phenol resin is compared with a typical alkaline phenol under three conditions: (1) continuous exposure at 80° F. and 65 percent relative humidity, (2) exposure to repeated cycles of soaking and drying, and (3) continuous exposure at 158° F. and 20 percent relative humidity. The acid-type phenol failed to produce joints comparable in strength to those obtained with the alkaline-type glue, and, although no further deterioration was evident throughout 30 months of exposure to moderate humidity at 80° F., to the soaking-drying cycle, or to high temperature and low humidity, the original difference in joint strength remained.

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strength was retained throughout the test period. Since the veneer used was matched for both glues, the high percentages of wood failure retained throughout all exposures indicate damage to the wood by the acid-catalyzed glue.

When the resins were partially cured at 140° F. for 16 hours, the differences between alkaline- and acid-catalyzed intermediate-temperature phenols were not so great, but damage to the wood by the acid-catalyzed phenol was evident. 3

Fortified urea resins. --Fortified urea resins may be classified as melamine-urea or as resorcinol-urea resins on the basis of the type of fortifier added to the urea-formaldehyde resin. The curves shown in figures 1 to 10 for fortified urea resin average values obtained for glues of this entire class. Differences between the performance of a melamine-urea resin glue and a resorcinol-fortified urea resin glue over a period of 18 to 30 months of exposure to high temperatures and to high humidity are shown in figure 15. These data, which can be compared with similar data for other glues in figures 1 through 10, indicate that the melamine urea resin glue was generally more durable than the resorcinol-fortified urea resin glue. The melamine-urea tended to approach the performance of the straight melamine- and phenol-resin glues during the relatively short exposure of 18 months.

More extensive studies of the performance of these two types of glues in birch plywood have since been made. 7 A series of laboratory-formulated glues containing different proportions of each fortifier with the urea resin were exposed under controlled conditions over a 4-year period. Results indicated that incorporation of at least 20 percent of melamine resin or 10 percent of resorcinol with added paraformaldehyde in the urea resin distinctly improved the performance of birch plywood under continuous exposure at 158° F. and 20 percent relative humidity, and under repeated cycles of high and low humidity at 80° F. Fortification was least effective under continuous exposure at 80° F. and 97 percent relative humidity. Generally, the improvement with either melamine resin or resorcinol fortifier was in direct proportion to the amount of fortifier included, the most significant improvement being noted between the straight urea resin and the lowest amount of fortifier of each type. The performance of glues containing the highest proportions of each fortifier was almost as good as that of the straight melamine-resin glue.

Weathering Tests of Plywood Panels

Tests of unprotected plywood panels subjected to weathering have provided data on the durability of five types of glues under the variable conditions of outdoor exposure. Plywood test panels, 24 inches square, that were made of different species and different thicknesses of veneer, have been exposed since 1936. Records of their first 10 years of performance have been recorded. An equal number of yellow birch, yellow-poplar, and Douglas-fir panels was included in these tests, Three-ply panels were made from 1/16-inch veneer, and 5-ply panels from 1/8-inch veneer. Each panel has been visually inspected at regular intervals and rated on the basis of the integrity of the glue joints. The percentage of open joint area and the percentage of wood failure were considered in arriving at the rating for each glue shown in figure 16. The glues included in these tests, in order of decreasing durability, were as follows: hot-press phenol, intermediate-temperature phenol, room-temperature-setting and hot-press urea resins, and casein (without preservative). The relatively high rating of the hot-press and intermediate-temperature phenols indicates their superiority by a considerable margin over the urea resins. The intermediate-temperature phenol rating is based on one glue of the acid type that was cold-pressed and later cured in a kiln at 155° F. for 24 hours.

Exposure Tests of Laminated Beams

The durability of several glues has been studied by exposing laminated beams to various conditions over periods up to 5 years. Casin and room-temperature-setting urea resin were used to glue 9 laminations of nominal 1-inch southern yellow pine and Douglas-fir lumber into beams 7 by 7 inches in cross section and 5 feet 4 inches long. An early acid-type phenol resin was also included in these tests, but results obtained with this glue are not presented since they are not typical of modern intermediate-temperature phenols. The beams were glued at approximately 12 percent moisture content, and were subjected to several conditions, including outdoor exposure and exposure in an unheated shed. Similar southern yellow pine and Douglas-fir beams, in tests including casein containing 10 percent pentachlorophenol as an additional glue, were exposed continuously at 80° F. and 97 percent relative humidity. In the latter test, redwood heartwood beams were also glued with casein containing no preservative to determine whether the greater durability of redwood had any effect on the durability of glue joints. At intervals, sections were removed from the ends of these beams, and block-shear specimens were prepared and tested, after they were reconditioned to approximately 12 percent moisture content, to determine the strength of the glued joints.
In a more recent and extensive study to determine the suitability of various glues for laminating white oak and other species for boat timbers and other purposes involving severe exposure, several hundred beams 4 feet long and usually 6 by 6 inches in cross section were laminated with intermediate-temperature phenol, resorcinol, and melamine-resin glues and cured at various temperatures. Sections from these beams were tested while dry to determine the original shear strength of the glue joints. Other sections were immersed in salt water to determine the effect of continuous soaking in salt water upon the strength of the glue joints. The beams themselves were placed on outdoor exposure racks without protection, except that one end was painted. At intervals, a short section was removed from the painted end to provide material for shear testing, and the cut end was repainted before further exposure. The unpainted end was inspected regularly for evidence of delamination.

### Results of Laminated Beam Exposure Tests

**Exposure to covered, unheated conditions.** --The durability of joints made with casein (without preservative) and room-temperature-setting urea resin and exposed to covered, unheated conditions for periods up to 5 years is shown in table 2. Under these conditions, no definite indication of loss of joint strength with prolonged exposure is evident.

**Continuous exposure at 80° F. and 97 percent relative humidity.** --Data obtained in these tests are presented in table 3. After 6 months’ of exposure, casein without preservative failed to show appreciable strength with any of the 3 species tested. The greater resistance of redwood to decay had no apparent effect on the rate of joint strength loss. Casin glue containing 10 percent pentachlorophenol showed a remarkably increased durability, particularly in the Douglas-fir heartwood beams, which still retained nearly 80 percent of their original joint strength after 5 years. Joints in the less durable southern yellow pine sapwood beams were effectively protected by the preservative for less than 1 year under this condition of exposure, which was extremely favorable to mold and other fungus development. The difference in effectiveness of the preservative between pine and Douglas-fir may have been due in part to the difference in moisture content, which was consistently about 2 percent lower in the Douglas-fir. The room-temperature-setting urea resin maintained good joint strength for about 1 year, but decreasing amounts of wood failure confirm the evidence of progressive weakening of this glue at 97 percent relative humidity and 80° F. shown by the Laboratory plywood exposure tests.
Exposure to outdoor conditions. --Under outdoor exposure, casein and urea-resin glues showed a tendency toward decreasing joint strength during the 5-year exposure period, as shown in table 4. Urea-resin glued joints lost strength at approximately the same rate in southern yellow pine and Douglas-fir. After 5 years of exposure, the joints retained between 30 and 40 percent of their original strength, but the beams showed serious amounts of delamination. Southern yellow pine beams glued with casein were completely delaminated after 4 years. In Douglas-fir, casein-glued joints still retained high strength values after 5 years of outdoor exposure, but considerable delamination had developed in these beams.

The difference in durability of casein-glued joints between Douglas-fir and southern yellow pine may have been due to differences in moisture content observed throughout the period of exposure. Although all beams were glued at approximately 12 percent moisture content, the range of moisture content throughout the exposure period varied as follows: southern yellow pine, 14.4 to 30.0 percent; Douglas-fir, 11.9 to 18.9 percent. The higher moisture content in the pine beams favors the development of molds and other micro-organisms known to be detrimental to casein glue. It appears that the lower moisture content that prevailed in the Douglas-fir was sufficient to prevent this form of deterioration in casein glue, which is known to cause rapid loss of joint strength at moisture content values above about 20 percent.

Results of the study involving the determination of joint strength and measurement of delamination in beams of white oak, Douglas-fir, and southern yellow pine after exposure to the weather and to fresh and salt water confirm, in general, the durability of intermediate-temperature phenol, melamine, and resorcinol glues as determined from tests of plywood. Resistance to delamination while exposed outdoors was found to be a more critical test of glue-joint durability than retention of joint strength under continuous soaking in either fresh or salt water. These tests also showed that resin glues of the intermediate-temperature phenol, melamine, and resorcinol types need a more complete cure to develop maximum resistance to delamination in timbers than is indicated by plywood tests.

Typical measurements of delamination taken at intervals throughout an exposure period of 36 months on white oak beams glued with an intermediate-temperature phenol resin cured at temperatures of 110°, 160°, 180°, and 210° F. are shown in figure 17A. Similar results for a resorcinol-resin glue cured at 80°, 110°, and 140° F. are shown in figure
17B. Curing at lower temperatures is generally adequate to produce a comparable degree of resistance to delamination in lower density species. Delamination and joint-strength data have established the fact that certain intermediate-temperature phenol, melamine, and resorcinol resins, when properly used and cured, are capable of producing glue joints that develop the full strength of the wood, either wet or dry, and maintain sufficient strength to avoid appreciable delamination under prolonged periods of exposure to weathering without protection.

Summary

Various methods of determining the durability of glues have been reviewed, and comparisons have been made of hot-press and intermediate-temperature phenol resins, hot-press melamine resins, resorcinol resin, fortified hot-press, hot-press, and room-temperature-setting urea resins, casein, animal, and vegetable (starch) glues on the basis of these tests. Most of the data available have been secured from Forest Products Laboratory tests of birch plywood specimens involving 10 constant and 10 cyclic exposures to moisture and to low and high temperatures. Additional information has been supplied by exposure tests of plywood panels of different wood species, by exposure tests of laminated beams, and by accelerated tests of various sorts.

The durable nature of the phenol resins is evident under all conditions of exposure used in these tests. In general, the strength of the glue joint is largely limited by the ability of the wood itself to resist the conditions of exposure. In the intermediate-temperature phenols, however, pronounced differences exist between certain alkaline and acid glues. When fully cured through the application of heat, the more acid glue appears to cause deterioration of the wood, with resultant low joint strength, although high percentages of wood failure are maintained. The alkaline-catalyzed intermediate-temperature phenol glues do not show this effect.

Resorcinol and hot-press melamine glues withstand severe conditions of exposure to heat and moisture, and appear to be similar to phenol resins in durability.

Most forms of urea-resin glue are moderate to low in resistance to exposure at high humidities and ordinary temperatures, and low in durability under conditions involving high temperature, especially combinations of high temperatures and high humidities. The effect of high
temperature is most severe in room-temperature-setting urea resin, and decreases in severity with the hot-press and fortified urea-resin types. Under continuous exposure at 158° F., room-temperature-setting urea resin was the least durable glue tested, whereas urea resins containing equal or larger proportions of melamine or resorcinol resin tend to approach but not equal the durability of phenol resins. Room-temperature-setting urea resins are more acid than other glues of the urea-resin type, and many of them appear to lose appreciable strength over a period of 3 years when merely aged at 80° F. and 65 percent relative humidity. All urea-resin glue types in birch plywood are good to high in their resistance to continuous soaking at room temperature and to soaking-drying cycles, but cycles of low and high humidity and exposure to weather cause more rapid deterioration of most of these glues. Urea resin highly fortified with melamine resin appears to be comparable to phenol resin in resisting cycles of high and low relative humidity.

Room-temperature-setting urea resins, when used with certain woods such as yellow birch, failed when continuously soaked in salt water. With other species such as oak, room-temperature-setting urea resins failed to withstand prolonged immersion in either fresh or salt water. Flour-extended urea resins are moderately reduced in resistance to soaking, and the degree of reduction depends upon the amount of flour extension. Attack by molds under high humidity conditions is evident even for urea resins that contain only small amounts of flour extender, however, and deterioration under these conditions is very rapid in the case of highly-extended urea glues.

Casein glue without preservative lacks durability under all conditions of exposure to weathering or to relative humidity above 90 percent. Casein shows good resistance to high temperatures. The inclusion of preservative chemicals, such as chlorinated phenols, increases the durability of casein-glued joints at high relative humidities without apparent detrimental effects on durability in other respects. The effect, however, is somewhat temporary. Inclusion of such chemicals does not in itself assure permanence when exposed continuously over a period of years to warm, damp atmospheres.

Animal and vegetable (starch) glues maintain good strength in wood for long periods of time as long as the wood remains dry. These glues are not resistant to moisture, and deteriorate rapidly when exposed to relative humidities above 80 percent.

Where service conditions are such that durability under extremes of high and low humidity and in cycles involving high temperature is important,
and where methods of applying sufficient heat are available, the hot-press and intermediate-temperature phenol resins, hot-press melamines, and resorcinols offer the most satisfactory durability characteristics of the glues that have been tested.

In many operations, the selection of glue is limited to those that set at room temperature. Of the room-temperature-setting glues included in these tests, casein without preservative is not durable under cycles involving high humidity due to its low mold resistance, although when suitable preservative chemicals are added the resistance of this glue to molds is improved. Room-temperature-setting urea resin loses strength under exposures involving high relative humidity at room temperature. Under continuous exposure at 97 percent relative humidity and 80°F, neither joints bonded with urea-resin nor those bonded with casein, with or without preservative, can be relied upon to remain permanently strong over a period of years. In resistance to exposures involving high temperatures, the superiority of casein over room-temperature-setting urea resin is clearly shown. When service conditions involve occasional or frequent soaking in addition to high temperature and extreme humidity exposures, neither casein nor room-temperature-setting urea glue appears to be satisfactory. The maximum degree of durability available at room temperatures is provided by the resorcinal resins. Although resorcinol resins are not fully cured at room temperatures and may require beating to somewhat elevated temperatures for certain critical uses, such as in white oak boat timbers, glues of this type cured at room temperature are highly durable in plywood specimens under all conditions of exposure used in these tests.
Table 1. -- Comparative resistance of a commercial casein glue with and without preservative as measured by tests of standard yellow birch plywood shear specimens after exposure to conditions favorable to mold development

<table>
<thead>
<tr>
<th>Glue</th>
<th>Plywood shear strength and percentage of wood failure</th>
<th>After exposure in mold tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>: Original:</td>
<td>Wet after:</td>
</tr>
<tr>
<td>Casein without preservative</td>
<td>407-26</td>
<td>178-1</td>
</tr>
<tr>
<td>Casein plus 5 percent pentachlorophenol²</td>
<td>346-6</td>
<td>253-4</td>
</tr>
<tr>
<td>Casein plus 5 percent sodium pentachlorophenate³</td>
<td>404-15</td>
<td>240-1</td>
</tr>
<tr>
<td>Casein plus 5 percent sodium (2, 4, 5) trichlorophenate³</td>
<td>427-38</td>
<td>204-3</td>
</tr>
<tr>
<td>Casein plus 5 percent sodium tetrachlorophenate³</td>
<td>409-28</td>
<td>178-0</td>
</tr>
</tbody>
</table>

¹The first value represents joint strength in pounds per square inch; the second value represents the percentage of wood failure. Each value represents an average of eight shear-test results.
²Mold test as described in Forest Products Laboratory Report No. 1344, revised
³Based on dry weight of glue powder.
Table 2. -- Durability of joints in unpainted laminated beams exposed to unheated conditions while covered

<table>
<thead>
<tr>
<th>Exposure period</th>
<th>Southern yellow pine</th>
<th>Douglas-fir</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average shear strength</td>
<td>Average shear strength</td>
</tr>
<tr>
<td>Months</td>
<td>P. s. i.</td>
<td>Percent</td>
</tr>
<tr>
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<td>91</td>
</tr>
<tr>
<td>6</td>
<td>1,603</td>
<td>93</td>
</tr>
<tr>
<td>12</td>
<td>1,729</td>
<td>70</td>
</tr>
<tr>
<td>18</td>
<td>1,821</td>
<td>86</td>
</tr>
<tr>
<td>30</td>
<td>1,559</td>
<td>88</td>
</tr>
<tr>
<td>48</td>
<td>1,589</td>
<td>86</td>
</tr>
<tr>
<td>60</td>
<td>1,612</td>
<td>84</td>
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</table>

CASEIN WITHOUT PRESERVATIVE

ROOM-TEMPERATURE-SETTING UREA RESIN

<table>
<thead>
<tr>
<th>Months</th>
<th>P. s. i.</th>
<th>Percent</th>
<th>P. s. i.</th>
<th>Percent</th>
</tr>
</thead>
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<tr>
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<tr>
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<td>98</td>
<td>1,621</td>
<td>98</td>
</tr>
<tr>
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<td>85</td>
<td>1,757</td>
<td>85</td>
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<tr>
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<td>93</td>
<td>1,287</td>
<td>94</td>
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Report No. 1530
Table 3. -- Durability of joints in unpainted laminated beams continuously exposed to 97 percent relative humidity and 80° F.

<table>
<thead>
<tr>
<th>Exposure period</th>
<th>Southern yellow pine Average shear strength</th>
<th>Douglas-fir Average shear failure</th>
<th>Redwood Average shear strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months</td>
<td>P. s. i.</td>
<td>Percent</td>
<td>P. s. i.</td>
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<td>97</td>
<td>1,701</td>
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<tr>
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<td>77</td>
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<tr>
<td>18</td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>48</td>
<td></td>
<td></td>
<td>0</td>
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<tr>
<td>60</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

CASEIN WITHOUT PRESERVATIVE

CASEIN PLUS 10 PERCENT PENTACLOROPHENOL

ROOM-TEMPERATURE-SETTING UREA RESIN

Report No. 1530
Table 4. Durability of joints in unpainted laminated beams under outdoor exposure

<table>
<thead>
<tr>
<th>Exposure period</th>
<th>Southern yellow pine</th>
<th>Douglas-fir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average shear strength</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>Average shear failure strength</td>
<td>:</td>
<td>:</td>
</tr>
</tbody>
</table>

CASEIN WITHOUT PRESERVATIVE

<table>
<thead>
<tr>
<th>Months</th>
<th>P.s.i.</th>
<th>Percent</th>
<th>P.s.i.</th>
<th>Percent</th>
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</thead>
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<tr>
<td>60</td>
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<td>0</td>
<td>1,224</td>
<td>80</td>
</tr>
</tbody>
</table>

ROOM-TEMPERATURE-SETTING UREA RESIN

<table>
<thead>
<tr>
<th>Months</th>
<th>P.s.i.</th>
<th>Percent</th>
<th>P.s.i.</th>
<th>Percent</th>
</tr>
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<tbody>
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<td>1,664</td>
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<td>871</td>
<td>89</td>
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<tr>
<td>48</td>
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<tr>
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<td>462</td>
<td>39</td>
<td>640</td>
<td>62</td>
</tr>
</tbody>
</table>

Report No. 1530
Figure 1.--Resistance of birch plywood joints, glued with eight types of glues, to continuous soaking in water at room temperatures.
Figure 2.--Resistance of birch plywood joints, glued with eight types of glues, to continuous exposure at 97 percent relative humidity and 80° F.
Figure 3.--Resistance of birch plywood joints, glued with eight types of glues and exposed to a repeating cycle of 2 days’ soaking in water at room temperature followed by 12 days’ drying at 80° F. and 30 percent relative humidity.
Figure 4.--Resistance of birch plywood joints, glued with eight types of glues, and exposed to a repeating cycle consisting of 2 weeks in 97 percent relative humidity at 80° F., followed by 2 weeks in 30 percent relative humidity at 80° F.
Figure 5.--Resistance of birch plywood joints, glued with eight types of glues and kept under continuous exposure at 80°F. and 65 percent relative humidity.
Figure 6.--Resistance of birch plywood joints, glued with eight types of glues and exposed continuously at 158° F. and 20 percent relative humidity.
Figure 7.--Resistance of birch plywood joints, glued with eight types of glued and exposed continuously at 158° F. and 60 percent relative humidity.
Figure 8.--Resistance of birch plywood joints, glued with eight types of glues and exposed to a repeating cycle of 8 hours at 158° F. and 20 percent relative humidity followed by 16 hours at 80° F. and 65 percent relative humidity.
Figure 9.--Resistance of birch plywood joints, glued with eight types of glues and exposed to a repeating cycle consisting of 8 hours at -20° F. followed by 16 hours at 80° F. and 65 percent relative humidity.
Figure 10. -- Resistance of birch plywood joints, glued with eight types of glues, and exposed continuously at 200°F. and 20 percent relative humidity.
Figure 11.--Resistance of birch plywood specimens, glued with different cold-setting urea-resin glues, to (A) continuous exposure at 80° F. and 65 percent relative humidity, (B) repeated cycles of alternating high (97 percent) and low (30 percent) relative humidity at 80° F., (C) continuous exposure at 158° F. and 60 percent relative humidity, and (D) repeated cycles of exposure at room temperature and 158° F.
Figure 12.--Resistance of birch plywood specimens, glued with unextended and rye-flour-extended hot-press urea resin, to (A) continuous soaking, (B) repeated cycles of soaking and drying, (C) continuous exposure at 80° F. and 97 percent relative humidity, and (D) repeated cycles of high (97 percent) and low (30 percent) relative humidity.
Figure 13.—Resistance of birch plywood joints, glued with different casein glues, with and without the addition of pentachlorophenol under (A) continuous exposure at 80°F. and 97 percent relative humidity, (B) continuous exposure at 80°F. and 65 percent relative humidity, and (C) continuous exposure at 158°F. and 60 percent relative humidity.
Figure 14.--Resistance of birch plywood joints, glued with alkaline and acid intermediate-temperature phenol resin, under (A) continuous exposure at 80° F. and 65 percent relative humidity, (B) repeated cycles of soaking and drying, and (C) continuous exposure at 158° F. and 20 percent relative humidity.
Figure 15.--Resistance of birch plywood joints, glued with melamine- and resorcinol-fortified urea resins, under (A) repeated cycles of exposure to high and low humidity, B repeated cycles of exposure at room temperatures and 158° F., (C) continuous exposure at 158° F. and 60 percent relative humidity, and (D) continuous exposure at 200° F. and 20 percent relative humidity.
Figure 17.--Resistance to delamination of glue joints in white oak beams cured at various temperatures and exposed to the weather without protection, (A) intermediate-temperature phenol-resin glue, (B) resorcinol-resin glue.