Durability of Adhesives in Plywood

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Abstract

Seven different adhesives were evaluated for durability as plywood adhesives by exposing panels and shear-test specimens to weathering at the Madison exposure site for nearly 8 years. Wet-strength loss and wood-failure changes were measured as a function of exposure time. The method of exposure accelerated the degradation that would have resulted from exposure in most service environments. Results were compared qualitatively with the information obtained by accelerated aging in the laboratory and analyzing wet-strength loss as a rate process. The rapid, initial strength loss that had been observed with acid-catalyzed adhesives on Douglas-fir by dry-heat aging in the laboratory was also detected in their behavior on the test fence. The tendency for some adhesives to hydrolyze during laboratory aging by water soaking was also reflected in test-fence performance. A more precise measure of a correlation between test-fence results and laboratory-derived data was not possible because of the high variability in the shear-strength values.

HOW LONG will a wood product bonded with adhesives last in service? This is the question that is invariably asked about adhesives, particularly when a bonded product is expected to perform satisfactorily for many years in severe environments. Attempts to answer the question by simulating and accelerating the aging. process have been many and varied. Each development of a new method for accelerated aging is accompanied by yet another question, "How do the results from this accelerated aging correlate with the adhesive's behavior in service?"

The questions are simple and straightforward, but the answers are complex, imprecise, and fraught with uncertainty. This is due in large part to problems in measuring some important property of a joint, to the inherent variability in the materials, and to a lack of agreement about what constitutes reasonable service conditions. It might be anticipated that these problems could he minimized by judicious use of modern testing equipment, by ingenious experimental designs with sophisticated statistical treatments, and by carefully defining service conditions. But the fact remains that compromises must be made between what might be considered theoretically correct and desirable and what is physically possible experimentally,

In the present study, the adhesives were evaluated in plywood joints. Plywood was selected as the test material because both hot-pressed and cold-pressed adhesives could be readily used, the plywood shear test specimen was a well-recognized standard, and large numbers of specimens could be easily produced from panels carefully processed in the laboratory. The specimens and panels were assigned to the various exposure conditions on a random basis.

The general plan was to measure wet-shear-strength changes with time of exposure to a variety of carefully controlled conditions, and to determine the rate of loss and locus of failure in each case. The laboratory exposures used elevated temperatures to accelerate the degradation process, with the specimens exposed continuously to carefully controlled conditions. The intent was to learn something about the mechanism of degradation of each adhesive and to determine the effect of temperature on the rates of degradation. From this information, an estimate could be made of the degradation rate at some selected service temperature, Such an estimate would be based upon the assumption that the material was exposed continuously to the selected temperature, realizing that this is seldom, if ever, true in service.

Service environments generally impose a cyclic swelling and shrinking stress on gluelines. This effect varies from one environment to another, as well as being influenced by the manner in which materials are exposed in any one environment. Correlating laboratory-derived results with behavior in service environments involves judging the relative importance, for each adhesive, of the three major causes of

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degradation: thermal degradation, hydrolysis, and swelling and shrinking stresses. Service environments and exposure methods need to be defined on the basis of the same three degrading influences with at least a qualitative assessment of which one is dominant.

In the present study, the service environment was selected to be relatively severe. This was the outdoor exposure fence at the Forest Service exposure site, Madison, Wisconsin, where temperatures can range from well below freezing to 100°F with frequent precipitation that averages 30 inches annually. The materials were exposed both as unpainted panels and as precut shear-test specimens. Previous experience (2) had shown that plywood in these two forms experienced a wide range of moisture content (MC) changes during exposure at the site, with the separate specimens exhibiting a greater change than did the panels. This selection of material and method of exposure was expected to accelerate the rate of degradation over that in material to which finishes had been applied or which was partially protected from rain and sun. The intent was to accelerate degradation rather than to simulate any specific end-use condition. The results, therefore, cannot be translated into performance at any service environment but simply represent what might occur under a quite severe exposure situation.

The purpose of this study was to determine if the differences noted among adhesives in laboratory-controlled accelerated-aging experiments (1, 3) were related to their performance during outdoor exposure.

It is important to note the difference for which the two methods were developed. While the test-fence exposure shows what did happen, the accelerated-aging technique is intended to allow a prediction of what will happen. The accelerated-aging experiments had been developed to measure rates of shear-strength loss and changes in wood-failure values, or locus of failure, by viewing these changes as a rate process. The accelerated aging was designed to evaluate essentially two different phenomena that influence degradation; namely, dry heat (3) and hydrolysis (1).

The dry-heat experiments revealed that all adhesives evaluated resisted thermal degradation as well as or better than either yellow birch or Douglas-fir. However, the adhesives requiring acid catalysts for curing produced bonds that lost strength rapidly during the initial stage of heating, followed by a stage of slower rate of lass with prolonged heating. This initial strength loss could be as high as 50 percent, as for example, when Douglas-fir was bonded with an acid-catalyzed phenolic adhesive. Dry-heat exposures evaluated whether or not the acidity of the adhesive system, coupled with the natural acidity of the wood, could degrade wood strength at the wood-adhesive interface. Earlier work had shewn that this potential loss of strength was realized even under prolonged storage at normal room temperatures and humidities.

Work with the same adhesive systems in water-soaking experiments (1) had clearly demonstrated the stability to hydrolysis of the hot-press phenol, the resorcinol, and the acid-catalyzed phenol. These three adhesives were in a class by themselves, showing only slow rates of strength loss, and the strength loss was in the wood rather than in the adhesive. Subsequent work showed that the catalyzed polyvinyl acetate adhesive responded in a similar fashion.

The water-soaking experiments showed the melamine adhesive to be susceptible to hydrolysis, the melamine-urea adhesive to be even more sensitive, and the urea to hydrolyze most rapidly. The water-soaking experiments ranked the adhesives in the same order as would be expected from previous experience and observations obtained with similar adhesives in service.

Experimental Procedure

Three-ply panels of yellow birch and Douglas-fir were prepared from 1/8-inch-thick veneers selected for freedom from defects, freedom from short grain, smoothness, and straightness of grain. Seven different adhesives were used to bond the panels in accordance with the recommendations of the adhesive manufacturer. The details of panel and specimen preparation and assignment to different exposure conditions were reported earlier (1, 3).

The plywood was exposed at the Madison site, starting in the period 1964 to 1966, on racks slanting 30° from the vertical facing south. This provided maximum opportunity for exposure to the sun and for wetting by precipitation and condensation. The plywood was exposed both as panels and as individual precut shear test specimens (Fig. 1).

At various intervals over 7-1/2 years, five specimens and one panel representing each adhesive-species Combination were removed for test. The specimens represented a random selection from among those cut from all panels that had been prepared. The specimens cut from the panels, however, represented only that single panel. Ten specimens were cut from the center of each panel, discarding approximately a 1-inch trim from the edges.

Before test, some of the specimens (five exposed as specimens and five from the exposed panel) were subjected to a vacuum-pressure soak (1), and tested for shear strength and wood failure in the wet condition.

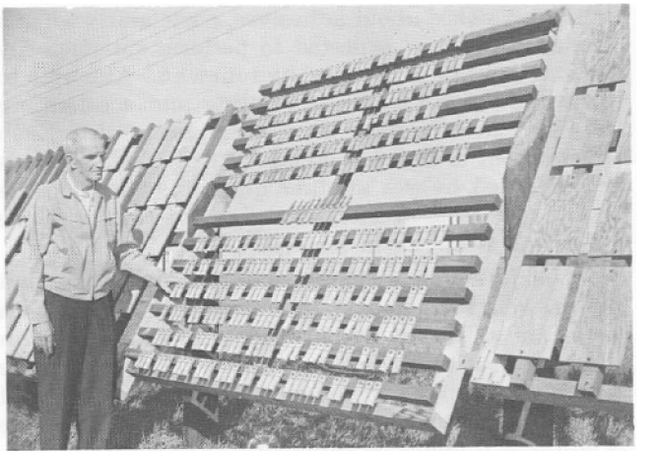

Figure 1. – View of the plywood panels and precut shear test specimens on exposure at the Madison exposure site.

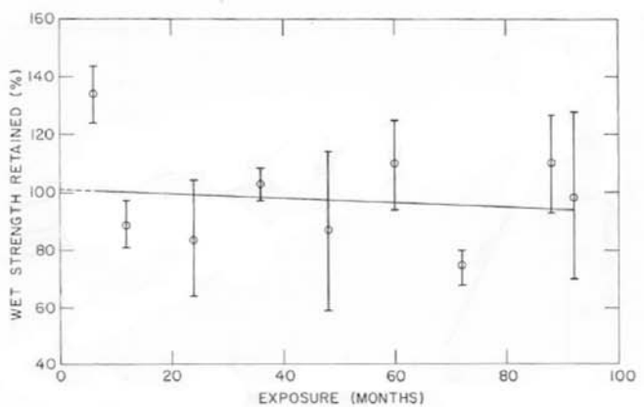

Figure 2 – Straight line shows change in wet-shear strength over nearly 8 years of test-fence exposure for Douglas-fir plywood panels bonded with a hot-pressed phenol adhesive Variability is indicated by the range at each exposure period.

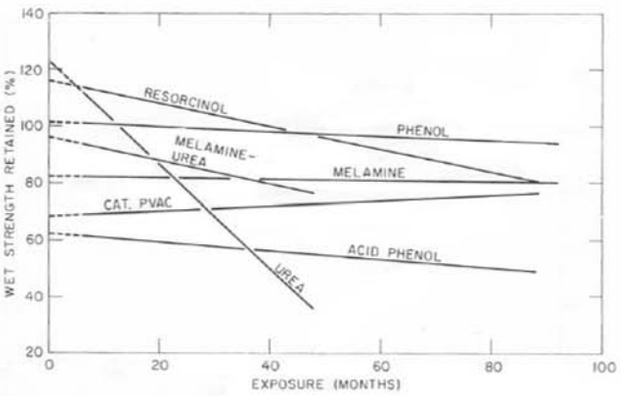

Figure 3. - Linear regression response of the change in wet-shear strength with time of exposure of Douglas-fir plywood panels bonded with seven different adhesives.

The remaining five specimens cut from the panel were tested in a dry condition as they came from the panel. The variability from the dry tests was greater than from the wet tests; the results are not reported here.

Results and Discussion

The most striking characteristic of the results was the high variability in the wet-shear-strength data. An example of the greatest variability resulted from testing the Douglas-fir specimens cut from the exposed panels. For the hot-pressed phenol adhesive the percentage wet shear strength retained was plotted against time of exposure (Fig.2). The vertical lines through the data points span the range of the 95 percent confidence limits. Figure 2 suggests the frustrations attending the analysis of rate-process data obtained from a test-fence exposure of adhesive bonds.

One approach to this variability problem was to average the total response of the panels to weathering by calculating a least squares regression line using the model equation

$$\log S_t = \log S_o - kt$$

where S_t is the webshear strength after aging, t is time, k is the rate of change of log S_t with time, and S_o is the shear strength at zero time obtained by extrapolation.

While mathematical analysis indicated that other models were needed to provide a better fit to some data, this linear function indicated the slope of the response and the position of the curves relative to each other. The zero-time shear-strength values of unaged specimens were not included in the calculation of the regression lines. The result of such calculations for the data in Figure 2 is the straight line showing the average response to weathering by phenolic-bonded panels over almost 8 years.

The regression lines for all adhesives evaluated from exposed Douglas-fir panels are shown in Figure 3. The urea-resin adhesive lost strength faster than did the other adhesives. Melamine-urea resin joints show the next fastest rates of strength loss, and then oddly enough, resorcinol. In other exposures (Douglas-fir plywood as precut specimens and yellow birch as both panels and precut specimens), resorcinol-bonded joints either degraded most slowly or exceeded only phenol-bonded joints. The increased rate may be linked to the increase in joint strength in the early stages of test fence exposure. This early increase was observed only in the specimens cut from exposed Douglas-fix panels. The reason for these effects was not apparent.

A rapid loss of strength occurred early in the exposure for both the acid-catalyzed phenol and the catalyzed polyvinyl acetate, since the extrapolated zero-time intercept showed only 62 and 68 percent retention of the zero-time strength of unaged specimens. The catalyzed polyvinyl acetate showed some strength increase on prolonged exposure, with the acid-catalyzed phenol degrading only slowly during the same period. The melamine, the hot-press phenol, and the resorcinol all retained 80 percent or more of their strength during the 7 to 8 years of weathering on a panel.

The changes in wood-failure values (Fig. 4), for the same series of specimens, add emphasis to the above indications. While Figure 4 refers to results on

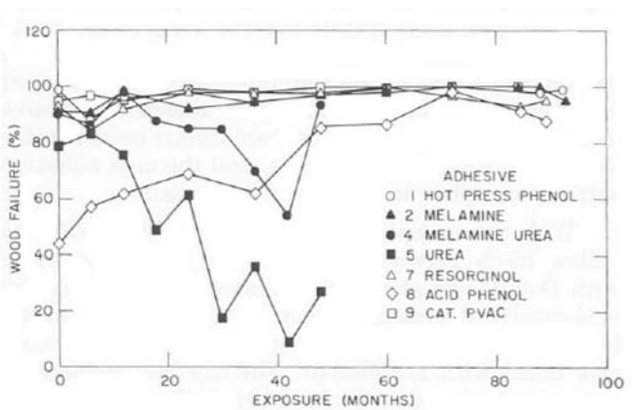

Figure 4. – Wood-failure change during nearly 8 years of exposure of Douglas-fir plywood panels bonded. with seven different adhesives.

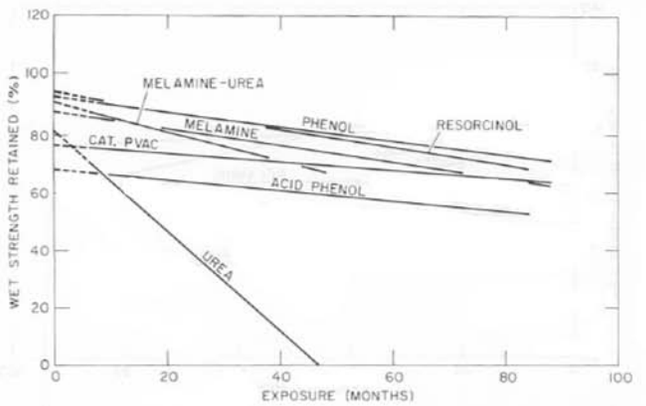

Figure 5. – Change in wet-shear strength during nearly 8 years of exposure as shear test specimens precut from Douglas-fir plywood bonded with seven different adhesives.

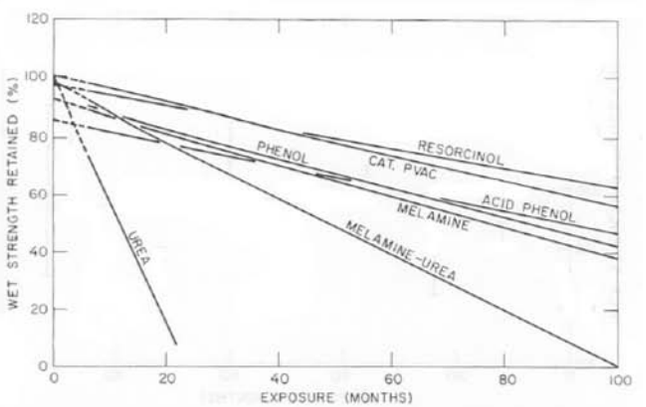

Figure 6. – Wet-shear-strength change during nearly 8 years of exposure of shear-test specimens precut from yellow birch plywood bonded with seven different adhesives.

Douglas-fir, those with yellow birch were similar. The hot-pressed phenolic, the resorcinol, the melamine, and the catalyzed polyvinyl acetate all had high wood failure initially (85% or greater), which was maintained throughout the exposure. Any strength changes were associated with changes in the wood. The acid-catalyzed phenol had a bond exhibiting low and shallow wood failure initially, and a gradual increase in the amount of wood failure as exposure progressed. The declining wood failure in the melamine-urea bonds with exposure time indicated loss of adhesive strength. A more pronounced wood-failure loss took place with the urea bonds as adhesive deterioration progressed.

The Douglas-fir plywood that had been exposed as precut shear-test specimens produced wet-strength results that were not as variable as those from the exposed panels. Figure 5 shows the linear regression lines for this aeries of specimens as wet-shear strength versus time of exposure, The most durable adhesives—hot-press phenol, resorcinol, melamine, and catalyzed polyvinyl acetate–retained 60 to 70 percent of their wet strength after 7 years of weathering. The changes were due to loss of strength in the woad, as high wood failures were noted throughout the exposure period. The acid-catalyzed phenol and the catalyzed polyvinyl acetate showed the greatest initial strength loss (extrapolated zero-time wet strengths of 68 and 76 percent of the zero-time strength of unaged specimens, respectively). The melamine-urea adhesive lost strength and percentage wood failure more rapidly than did the durable adhesives, and the urea adhesive suffered complete loss of bond in 4 years.

With one exception, the results obtained with the yellow birch plywood (Fig. 6) were similar to those with Douglas-fir plywood. The exception involves the acid-catalyzed systems, which do not show the initial loss of strength during the early exposure period that was noted with Douglas-fir. The dry-heat-accelerated aging in the laboratory also showed the acid catalyst effect to be more pronounced with Douglas-fir than with yellow birch.

Yellow birch joints degraded more rapidly than did Douglas-fir joints with all adhesives. Furthermore, the urea and melamine-urea bonds degraded mast rapidly on yellow birch (Fig. 6) just as they did on Douglas-fir (Fig. 5).

In general, wet strength losses were more rapid and extensive when the plywood was exposed as precut specimens than when exposed as panels with only the center portion sampled for test. Bond-strength losses with the more durable adhesives occurred two to four times faster when measured on precut specimens than when measured on specimens cut from panels. Even the urea and melamine urea bonds degraded faster when exposed as precut specimens, but the increased rate (approximately 1.5 times faster) was not as pronounced as when the locus of failure was predominantly in the wood.

Conclusions

The high variability of the wet strength results after exposing plywood panels and specimens to weathering precluded any statistical evaluation of the significance of the differences noted. Only patterns and trends could be observed and related to the results obtained by accelerated aging in the laboratory.

The results confirmed that the susceptibility of urea and melamineurea adhesives to hydrolysis governed their performance on the test fence, with the melamineurea adhesive being much more durable than the urea on both Douglas-fir and yellow birch. The tendency for the straight melamine adhesive to hydrolyze, as observed during accelerated aging in the laboratory, could not be detected during the 7 years of exposure.

The initial rapid strength loss exhibited by acid-catalyzed phenolic and catalyzed polyvinyl acetate adhesives (detected by dry-heat-accelerated aging) was also observed on the test fence with Douglas-fir plywood, but not with yellow birch.

The results verified that differences among adhesives, which could be determined by accelerated aging in dry heat as well as in water soaking, were

also observable in their performance during weathering.

Exposing unprotected plywood panels to weathering at the Madison site to maximize exposure to sun and precipitation accelerated degradation over that normally found in service environments. Significant loss of strength in the wood substrates occurred during the weathering period which would not have been the case when plywood is used in most service situations.

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