ACCELERATED AGING OF WOOD-BASED PANEL PRODUCTS:
A REVIEW AND COMMENTARY ¹/

Robert H. Gillespie ²/

Abstract.--The purpose of this report is to review how accelerated-aging procedures were developed to evaluate the durability potential of wood-based materials. It traces the development of accelerated-aging back to concerns about paper for library or archival storage and includes the procedures subsequently developed for wood, adhesives, plywood, particleboard, flakeboard, and other wood-based panel products. Viewing these procedures in the perspective intended by the original investigators should lead to a better understanding about their use and the information they provide and, thereby, guide and stimulate further developments in this area of research.

INTRODUCTION

Our more durable materials will survive years of natural weathering of the most severe variety. But the length of time required to bring about substantial change in physical properties in these materials is often longer than many investigators can devote to such evaluations. At the present time it must be recognized that there is no alternative to using accelerated-aging treatments to evaluate a wood product's potential durability. What is most needed is a better understanding of the procedures we now use and a willingness to continue the development of new and improved methods based as much as possible on sound scientific principles.

This report is an effort to correct some of the misunderstandings that prevail about durability evaluations, by tracing the historical development of some pertinent procedures, by defining purposes for their development and their relationship to performance classes, and by discussing different philosophies of approach. Durability evaluations pertinent to wood-based panels involve different adhesives, different forms of wood elements combined in many different ways, and different wood species.

The accelerated-aging procedures for this wide variety of wood-based composites will be presented in the chronological order of their development. While the emphasis may be on historical significance of these developments, different philosophies of approach, the purpose for their development, or their interrelationship to other procedures are interwoven throughout the report.

The purpose of accelerated aging is to evaluate a material or portion of a structure for its durability, serviceability, or long-term performance. These three terms all imply a design requirement being met or exceeded for a specified period in a particular service environment. Accelerated aging, therefore, becomes the means for generating information about durability—the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time (ASTM E 632).

The mere mention of accelerated aging raises images of doubt and cynicism in the minds of some investigators, and at least cause for concern in others. This is understandable, for accelerated aging most often means treatments that are more rugged than found in service environments. These treatments are considered by some investigators to be unrealistic and, consequently, inappropriate. Accelerated aging also often means short-term data collection with mathematical manipulation for long-term prediction—a process some investigators feel is no more justified than gazing into a crystal ball.

However, the investigators who initiated and refined the early accelerated-aging procedures were concerned about these same problems. They considered the appropriateness of different procedures and different alternatives and recognized the limitations and applicability of various treatments. Consequently, a review of developments in accelerated aging should be beneficial.

¹/ Paper presented at Workshop on Durability, Pensacola, FL, October 5–7, 1982.
²/ Author is a Supervisory Research Chemist at the Forest Products Laboratory, Forest Service, U.S. Department of Agriculture, Madison, WI.
toward establishing an improved perspective and understanding. This should then form a firm foundation for further development and stimulate productive research in this field.

ACCELERATED AGING VS. NATURAL WEATHERING

Ideally, an accelerated-aging procedure should evaluate a material during 1 to 2 months testing and provide results that would translate into accurate predictions of its behavior in natural weathering, as in some service environments. This ideal situation is seldom, if ever, achieved for a variety of reasons.

First among the many problems associated with correlations of this type is the lack of any definition or standard for weathering. Investigators spend much time and effort developing accelerated-aging procedures, carefully controlling exposure conditions, attempting to reduce variability in material response and, finally, establish a standard procedure. The investigators then ask questions such as, "If a material loses 25 percent strength during 10 cycles of this standard accelerated-aging procedure, how long would it last during natural weathering?" This would seem to be a logical and reasonable question except for the fact that natural weathering cannot represent a single, well-controlled, and repeatable set of exposure conditions.

Seldom, if ever, is a weathering exposure defined in terms of climate variables which would include the extremes, the means, and the frequency of departure from the means of temperature, wind velocity, precipitation, moisture condensation, solar radiation, etc. Climates are highly variable, totally uncontrollable, and seldom predictable. Efforts to correlate the effects of accelerated aging with those caused by exposure to one set of climate conditions hardly seem worthwhile in view of the elusive character of the weathering experience.

There are problems not only with variable climates but also with the manner in which materials are exposed to weathering. For example, small panels or specimens are exposed without finish or protection to maximize the amount of solar radiation impacting the surface. Most experiments with weather exposure are designed to accelerate the effects of weathering, not to approximate those effects. Thus, the conditions selected do not represent any expected service environment. There is no standard way of exposing materials to the elements of weathering. Consequently, the results of weathering studies cannot be translated into performance at any particular service environment. The variability among specimens often increases during weathering, which precludes any statistical evaluation of the significance of differences noted. Usually about the best that can be expected is that any patterns, trends, or rankings that develop during accelerated aging also take place when the same materials are exposed to natural weathering.

Another problem associated with correlations between accelerated aging and natural aging is the fact that strength losses for many materials during natural aging are not always continuous and linear with time of exposure. More strength is lost during summer than winter in northern climates and losses may slow up after 1 or 2 years exposure. For example, the natural weathering of phenolic-bonded flakeboards has shown a general pattern of rapid loss of strength and stiffness during the first year or two of exposure with a much slower rate of loss in subsequent years (WCMA 1966, 1970; Hann, Black, and Blomquist 1962, 1963; Jokerst 1968; and Clad and Schmidt-Hellerau 1965).

Performance Classes

There are those who feel that different performance classes of wood composites should be produced and the products differentiated by sensitive accelerated-aging tests. Most often the suggested performance classes are based upon the intended service environment for the product. While only problems associated with evaluating exterior-grade products will be considered in this report, it is important that the justification for this restriction be made clear.

It is claimed that performance classes allow different materials to be considered and permits them to be combined in the most economical way to meet certain end-use requirements. The argument is that expensive waterproof adhesives should not be used for products destined for mild service environments, since this not only increases costs but inhibits the development and use of alternative satisfactory adhesives. In a recent conference attended by investigators recognized as eminent in the field of wood composites (Oliver 1981), four different durability classes were suggested: (1) Open exterior, (2) protected exterior, (3) humid interior, and (4) dry interior.

While this approach to new product development is logical and laudable, there are obstacles to its full implementation, and arguments against it. Practical situations must be considered. Cost savings resulting from the use of a less expensive adhesive, reduction in adhesive spread, or inclusion of additional fillers and extenders could be rapidly eaten up by additional inventory costs, quality control costs, product identification and grade stamp costs, shipping and marketing costs, etc. Misuse during shipping, storage, and installation would increase with four distinctly different end-use grades to be readily recognized even after cutting so that all material becomes installed where intended. No provision can be made for accidental, but inappropriate, exposure to water from roof or plumbing leaks, or moisture condensation that often takes place even under the best attention to construction details. Because of these problems, it is almost impossible to define the micro-climates that would characterize each of the proposed exposure classifications. Furthermore, the development of test procedures that could be used to distinguish between product classes, including the development...
of satisfactory quality control tests for their manufacture, appears to be an almost insurmountable problem in light of our present capabilities for durability assessment.

Performance classes, based only upon the service environment for which a product is intended, represent many problems to the user of the product. In contrast, performance classes, based upon the end-use function in an assembly, are more readily understood by the user of the products. A performance concept that combines functional characteristics with service environments has been developed by the American Plywood Association for structural panel products to be used as wall, floor, and roof sheathing (Countryman 1980). The essential performance attributes of sheathing panels were identified as structural capacity, dimensional stability, and bond durability. A series of tests is recommended for measuring the mechanical properties important to structural capacity, and also for determining dimensional stability. Bond durability, which is planned for three levels—exterior, intermediate, and interior—will be measured by specific accelerated-aging tests. In all likelihood future developments in wood-based composites will emphasize multiple-criteria for end-use performance. They will probably be engineered or "tailor made" to perform a specific function in a particular service situation.

While it is important that accelerated-aging procedures are developed to distinguish between different durability levels, this report will concentrate on the most durable situation—full exterior weatherability without protection.

HISTORICAL BACKGROUND

The accelerated-aging procedures to evaluate the durability of paper and fiber building boards represent some of the earliest developments of such treatments. A review of the historical background surrounding these developments and how they evolved into present-day methods provides insight into the purpose for each development, the applicability and limitations each presents, and the need for further developments.

The most widely used accelerated-aging procedures for evaluating wood-based panel products in the United States is that described in ASTM D 1037 (1981); A—13\(^{\text{3/}}\) This standard method of evaluation is under the jurisdiction of ASTM Committee D−7 on wood and was published originally in 1949. The accelerated-aging procedure was incorporated in the original standard. Lewis (1956) summarized the procedures used at that time to test various building boards, and noted the fact that the accelerated-aging test had been developed by the National Bureau of Standards (NBS). The procedure was first mentioned in a series of reports on Building Materials and Structures, and was described by Jessup, Weissberg, and Weber (1938) in a report on accelerated aging of fiber building boards. It must be remembered that the NBS always had an active program of test method development and conducted research on building materials and other materials since its establishment at the turn of the century.

In 1937 Congress appropriated funds for NBS for a research program dealing with materials and methods of construction suitable for use in low-cost housing. This program involved many housing agencies in the Government, and particularly the Forest Products Laboratory, for studies of wood constructions. The plans for this program were described in the first report of the series by Dryden (1938) who helps describe the approach to accelerated aging with such statements as:

"Research is controlled, directed, and accelerated experience."

or

"Accelerated weathering tests made in a laboratory do not give results for many constructions which can be used to estimate the service life with reasonable accuracy. Such tests are, however, helpful because they indicate which constructions may be expected to give the longer service."

The accelerated-aging procedure developed by Jessup, Weissberg, and Weber (1938) was based on earlier work by Rasch (1931, 1933) evaluating the permanence of paper. Rasch had evaluated several accelerated-aging procedures and concluded that oven heating for 72 hours at 100°C (212°F) produced the same kind of changes in mechanical properties that took place during the natural aging of paper. Also; heating a variety of papers under these conditions reduced folding endurance and produced the same ranking as resulted from natural aging. This oven heating treatment of paper and folding endurance measurement remains as a standard method today (ASTM D 776−71; Tappi 1962).

Jessup et al. (1938) found that fiber building boards underwent little change in mechanical properties upon heating at 100°C (212°F), even for twice the time found useful for paper. They reasoned that a high humidity phase was needed to impose the effects of alternate wetting and drying, and chose a spray of condensing steam to help supply the moisture. They reasoned further that low temperatures encountered in certain localities sometimes caused moisture to condense and freeze within walls. Consequently, a freezing phase was added to the aging procedure. This resulted in a cycle that required 2 days to complete. These cycles were repeated for a total

\(^{3/}\) The conditions used for treatment in a laboratory procedure are shown in the Appendix with the procedures numbered sequentially.
of 300 treatment hours. This accelerated-aging treatment produced changes in the strength, permeability, and chemical composition of the boards being tested, and the changes were sufficiently large to permit classifying the boards into distinct groups. This met the objectives of the approach to accelerated aging which had been developed at NBS. The approach was:

"The materials are subjected to conditions which produce in a short time in the laboratory effects similar to those arising from long periods of natural aging. These conditions must be, of necessity, much more drastic than the deteriorating conditions encountered in use, in order to achieve results in a comparatively short time. However, experience with paper and some other materials has shown that a high order of stability to accelerated aging means satisfactory permanence, while low stability to accelerated aging means unsatisfactory permanence." (Jessup, Weissberg, and Weber 1938).

This accelerated-aging procedure was used to evaluate a number of commercial fiber building boards, comparing the results with those obtained upon 15 months exposure to outdoor weathering in the Washington, D.C. area (Jessup, Weber, and Weissberg 1940). The results showed a similarity in the changes of the physical properties resulting from the two aging treatments. It was concluded that the types of boards studied were not suitable for the exterior covering of buildings. The implication was that the accelerated-aging test was sufficiently severe to differentiate among boards that possessed exterior performance capabilities from those that did not.

This question of exterior versus interior serviceability of fiber boards apparently was of concern, because another less severe accelerated-aging test was developed during the same time period for use with sheathing papers (Weissberg, Jessup, and Weber 1939) and fiber sheathing boards (Jessup, Weber, and Weissberg 1941) (A-2).

These accelerated-aging procedures had a rather humble beginning. Those developing the procedures expected to learn how various materials performed with regard to their resistance to the effects of aging. Consequently, these methods were designed to provide an estimate of a material’s potential for satisfactory performance in service. From one viewpoint they might be considered procedures to qualify a fiberboard material for building purposes. Over the years these procedures were used to evaluate new products during their development stages. The procedures were widely accepted for such use, and confidence in the results continued to rise.

Several wood-based panel products achieved commercial success in the early 1940’s and voluntary commercial standards were developed to guide the manufacture of these products. These standards included: CS-42-43 (revised 1949) for Structural Fiber Insulating Board and R-179-63, a simplified practice recommendation for Structural Insulating Board (wood or core fiber); CS-112-43 for Homogeneous Fiber Wallboard; CS-176-51 (revised 1958) in Prefinished Wall Panels; CS-251-63 for Hardboard; and CS-236-61 (revised 1966) for Mat-Formed Wood Particleboard. Only one of these commercial standards has been converted into a new product standard—CS-42-49 became PS-57-73 for Cellulosic Fiber Insulating Board.

Most of these products were intended for interior applications, so the standards did not include an accelerated-aging test requirement. One exception was the 1966 revision of CS-236-61 for Mat-Formed Wood Particleboard provided for both a type 1 (interior) and type 2 (exterior) classification, while the original standard described only the interior product. The accelerated-aging procedure chosen to evaluate the exterior-type board was the 6-cycle exposure originated by Jessup et al. at the National Bureau of Standards.

Prior to the development of these commercial standards for the manufacture of panel products, the ASTM D 1037 test methods had been standardized for evaluating such products. These test methods had been in continuous use for product development purposes since their acceptance as standards. Because of this and because there had been no other efforts to develop meaningful procedures, it can be readily understood why the 6-cycle accelerated-aging test was adopted for the commercial standard. It was the only procedure that

---

4/ The 300 treatment hours were probably an approximation. The later version in ASTM D 1037 called for 6 cycles, each lasting 48 hours, for a total of 288 hours, or 12 days. The specimens were then removed after a drying cycle so they could be readily conditioned for mechanical property measurement.

5/ There have been changes over the years in the voluntary standards that may be used by industries for the manufacture of specific products. Commercial standards were under the jurisdiction of the Commodity Standards Division of the U.S. Department of Commerce until 1965. For example, CS-45-38, was a commercial standard, No. 45, assigned to Douglas-fir plywood, issued in 1938. The Department of Commerce later transferred the responsibility for the promulgation of standards to the Products Standard Section of the National Bureau of Standards. In 1974 any new standard or revision of old standards was converted to a product standard such as PS-1-74. The first of this series was for structural softwood plywood which combined commercial standards dealing with different softwood species. Currently, all standards are being revised and reissued by the American National Standards Institute. For example, CS-236, Mat-Formed Wood Particleboard, was never reissued as a product standard (PS No.) but has now been reissued as ANSI A208.1 (1979) (National Particleboard Association 1979).
had been used extensively, and earned a high level of confidence among investigators dealing with wood-based panel products. Although the 6-cycle procedure was too lengthy to serve as a quality control procedure for a manufacturing process, there was no suitable alternative that could be used with confidence. Research designed to develop such a suitable quality control procedure has been undertaken only during recent years.

**PREDICTING DURABILITY**

While there was essentially no change in the 6-cycle procedure to evaluate the durability of wood-based panel products during many years of use, further developments took place in the evaluation of paper in efforts to predict length of service. This is a simpler case than that of wood-based panel products because panel products are used in a wide variety of service environments, while paper is used primarily in the temperatures and humidities found in living spaces. Many of the same basic principles apply to either product.

Much of the concern about the durability of paper centered around book papers and archival storage. The problem was of national interest to libraries, and much of the early work was sponsored by the Virginia State Library with extensive investigations carried out by the W. J. Barrow Research Laboratory of Richmond, Va. By 1960, investigators were claiming as a first approximation that 3 days of heating paper at 100°C (212°F) gave results equal to about 25 years of natural aging (Hobbs 1960). A completely independent similar study in the Netherlands yielded an equivalent of 28 years of natural aging. From all these investigations on paper durability, it became very clear that most modern papers had a reasonable life expectancy of only about 50 years. On the other hand, papers from old books had been observed to survive natural aging for longer periods of time, more than 500 years in some cases (W. J. Barrow Research Laboratory 1964). W. J. Barrow concluded from his research that the reason for the poor durability of modern papers was the acidic nature of the paper resulting from the use of alum-rosin sizing in its manufacture. This led to the development of processes to deacidify existing papers so they might resist future degradation. It also led to the development of specifications for the manufacture of book papers that had a theoretical useful life of at least 300 years (Church 1960).

The prediction of this useful life resulted from extensive testing which involved heat treatment for as long as 48 days, with testing at different time intervals for fold endurance and tear resistance. It was found that the rate of deterioration of paper was not constant but decreased with time of heating. This led to the fitting of standard curves to the data so the comparison of one paper with another could be made with some statistical inferences. Also, estimates of strength beyond the point where the last test was actually measured could be made by cautious extension or extrapolation. This view of deterioration as a rate phenomenon materially improved the procedures for paper evaluation, and permitted significant progress to be made in the manufacture of durable materials. However, many important questions could not be answered until this rate-process approach was extended to measurements at several temperatures and application of the Arrhenius temperature-dependence relationship.

A hypothetical example of the determination of the Arrhenius temperature-dependence relationship is shown in figure 1. A physical property such as a strength property is measured periodically as a material that is exposed to three or more elevated temperatures, as depicted in figure 1A as T1, T2, or T3. The rate of property loss at each temperature may be expressed as a rate (k) or as the time to lose a specified amount of the original property, such as 25 or 50 percent.

The Arrhenius equation is usually written as:

$$\frac{dk}{dT} = \frac{E}{RT^2}$$

or

$$k = \frac{-E}{2.303RT}$$

where $k$ = the rate constant,

$E$ = the activation energy,

$R$ = the molar gas constant, and

$T$ = the absolute temperature.

A plot of the rates of property loss versus the reciprocal of the absolute temperature produces a straightline relationship such as is shown in figure 1B.

Multitemperature studies (Gray 1977) detected differences in the way temperature affected the deterioration rates of different papers. Papers often responded differently to changes in the temperature of aging. These differences were reflected in the activation energy as determined by the Arrhenius temperature-dependence relationship, where the logarithm of the rate of change in some selected property is plotted against the reciprocal of the absolute temperature to give a straight line. The slope of this line is a measure of the activation energy. The permanence of a paper in service could be predicted by extrapolation of the Arrhenius temperature-dependence relationship to the expected service temperature.

The Arrhenius equation evolved from kinetic studies of chemical reactions. There is a theoretical basis for applying the Arrhenius equation to the study of the deterioration of materials such as paper. Physical properties in paper change as a result of chemical changes. Therefore, the effects of hydrolysis, oxidation, or thermal degradation can be measured indirectly by measuring changes in physical properties.

However, in the degradation process, it must be recognized that (1) several chemical reactions
may occur simultaneously, (2) individual reactions can proceed at different rates, (3) reactions may not proceed independently of each other, (4) additional reactions may occur as the results of intermediates formed, and (5) rate constants can vary with temperature. Because of the complexity of the deterioration process from a chemical point of view, it is understandable why the activation energy might vary from one material to another. It is not surprising, therefore, that the slopes of the Arrhenius plots may differ considerably from one paper to another and that the regression lines may even cross over one another.

The attempts to correlate the results of single temperature-accelerated aging with natural aging were based on a false assumption—that changes in temperature affected the degradation of all materials equally. The early claims that 3 days of heating at 100°C (212°F) was equivalent to 25 years natural aging in one case and 28 years in another was simply coincidental. Values as low as 18.5 to as high as 63 years, depending on the activation energy, have since been reported (Roberson 1981).

The determination of a complete Arrhenius relation for any material is a long and somewhat tedious procedure. An obvious disadvantage to such multi-temperature rate studies is the increased time and cost of experimentation as compared with single-temperature, single dwell-time tests. However, the kinetic or rate-process approach to durability evaluation has become a valuable research tool to probe into the reactions and reaction mechanisms that characterize the aging of individual materials. The procedure can provide an understanding of the basic cause of deterioration in each case and yield realistic estimates of room-temperature degradation rates. Such rate-process studies are too time consuming and expensive to serve as quality control tests for a manufactured product, but their application to the evaluation of a product's response to degrading influences should suggest test conditions suitable for short-term quality control needs.

The durability of composites depends upon the durability of all components—the substrates, the adhesives, and the interfaces formed between adhesives and substrates during the manufacture of the composite. Over the years there have been many evaluations designed to emphasize adhesive durability, others specifically for substrate durability, and still others concentrating on the performance of a particular bonded-wood product. Each of these approaches to durability evaluation can supply valuable information, but no one set of tests can provide the answers to all the durability questions that arise.

WOOD DURABILITY

Some of the earliest work on the durability of wood was concerned with the effect of steaming or heating on the mechanical properties of different species. It was common practice to steam wood for various purposes, so it was desirable to know if different steam temperatures and treatment periods were detrimental to wood properties. Some of the most extensive research on this problem was carried out by J. D. Maclean (1951, 1953, 1954). This work was distinctive because it yielded information about how each mechanical property changed during the time of exposure. Rates of change were measured. This led to the use of multiple temperature, multiple dwell-time data from which activation energies could be calculated by way of the Arrhenius temperature-dependence relationship. Stammb (1956) collected and analyzed rate data on reaction kinetics, including data of MacLean (1951, 1953, 1954) and Rasch (1931, 1933). He compared how wood and various lignocellulosic components resisted thermal degradation, and he provided estimates of strength loss during kiln drying and during natural aging at room temperature.

ADHESIVE DURABILITY

The early work on evaluating the durability of different wood adhesives took a different tack. Prior to the introduction of adhesives based on synthetic resins in the 30's and 40's, practical wood adhesives were obtained from natural sources and used mainly for interior applications. The procedures that had evolved to evaluate their durability were, consequently, based on the interior conditions that might be met in service.

These exposures included extremes of temperature and moisture to which bonded wood products might be subjected, as well as conditions considered normal interior exposures—continuous and cyclic. A summary of the results of adhesive durability evaluations made over many years at the Forest Products Laboratory was published in 1944, with the last reprinting in 1963, following two revisions with additions (FPL 1963). There were six different continuous exposure conditions involving different temperature-humidity situations (A-3) and four combinations of cyclic conditions (A-4). The data were collected after different time-intervals of exposure so changes in shear strength and wood failure were obtained. In most cases data were obtained every 6 months, up to a total of 3 years of exposure, with more frequent testing under the more severe conditions. When the more durable adhesives from synthetic resins became available, time periods between tests were extended to as long as a full year, and in some cases requiring a total exposure time of 10 years to complete a test. These tests were discontinued in the early 1960's because the total exposure time required to evaluate durable adhesives was excessive.

Early in the 1960's, a meeting was held to assess future prospects for the wood industry with representatives of West Coast lumber associations, and scientists from industry, government, and universities in attendance. The attendees concluded that the outlook for the future was discouraging mainly because the long-term performance of any new bonded wood product, and
particularly any new adhesive potentially useful for wood bonding, could not be predicted with any reasonable degree of confidence. While it was recognized that the research task to resolve this problem was nearly impossible to accomplish, a small group of scientists agreed to tackle it in an unprecedented effort. Thus the Steering committee for the Accelerated Testing of Adhesives (SCATA) was formed. Over a period of about 9 years, this group met regularly to discuss the status of each element of the problem, to plan separate but coordinated attacks on the problem, and to assess progress of research as various studies reached completion. A brief summary of this efforts of SCATA was recently prepared by Marra (1981). This group made numerous contributions to a better understanding of durability assessment by accelerated aging and influencing and stimulating the direction of productive research on this subject for well over a decade.

Durability evaluation of adhesives has not been carried out on cured samples of adhesive alone with any consistent success. Efforts to do this so far have not been very productive. Most durability testing has involved bonded assemblies where the adhesive is confined in a thin bondline between wood substrates. Any durability evaluation consequently involves an adhesive-wood interface in addition to the adhesive itself. The question that always arises when evaluating adhesive durability is which wood species and joint configuration should be used. Attempts to develop standard procedures for adhesive evaluation resulted in ASTM D 905, Strength Properties of Adhesive Bonds in Shear by Compression Loading, and ASTM D 906, Strength Properties of Adhesives in Plywood-Type Construction in Shear by Tension Loading. ASTM D 905 specifies hard maple for the preparation of shear blocks, while ASTM D 906 specifies yellow birch veneer for preparation of Plywood specimens. These species were selected because of their high strength and fine, uniform texture. While these two ASTM procedures are normally followed for adhesive evaluations, some modifications have been incorporated in kinetic studies involving accelerated-aging and rate-process analysis.

The first kinetic studies with wood adhesives were carried out using yellow birch 3-ply plywood specimens prepared according to ASTM D 906 (Gillespie 1965, 1968; Gillespie and River 1975, 1976). The one exception to ASTM D 906 was to increase the thickness of veneers used for bonding into plywood panels. These kinetic studies demonstrated again that reasonable predictions of strength retention at room temperature could be made only by determining how changes in temperature affected the rates of thermal degradation or hydrolysis. This could be done only by multiple temperature, multiple dwell-time experimentation, and application of the Arrhenius temperature: dependence relationship. Additional kinetic studies designed to determine the precision of the method for predicting durability of adhesive bonds used hard maple shear blocks based upon ASTM D 905, except the bonded area per specimen was reduced to 645 mm² (1 in.²) from the specified 1,935 mm² (3 in.²) (Millett and Gillespie 1978; Millett, Gillespie, and Baker 1980), and the adherent thickness was also reduced. This change was made so that the required large number of specimens could be easily prepared, could be readily exposed without crowding in ovens and water baths with precisely controlled temperature, and would reach equilibrium conditions rapidly prior to strength tests. Small specimen testing was particularly required for kinetic studies to predict durability of adhesives because of the large number of specimens required for precise estimates. The results of the kinetic studies with shear block testing compared adhesive durability of bonded specimens with that of wood, using the time required for each to lose 25 percent of its original shear strength (Gillespie 1981). This behavior was shown to be equivalent to centuries of natural aging when wood was unaffected by fire, insects, or microorganisms.

These basic studies provided fundamental information about an adhesive's resistance to hydrolysis and thermal degradation. They supplied background data for use in comparing the behavior of any new adhesive with that of conventional adhesives of known durability and also with that of wood itself. New adhesives and wood species combinations could also be evaluated by these established procedures. From studies such as these, highly durable adhesives can be selected for use in new bonded wood products with assurance that both the adhesive and substrate would resist the chemical effects of aging. The remaining problem, which is associated with resistance to physical forces imposed upon the joints, then needs to be evaluated with the particular adhesive-species combination and specific joint geometry required for the product being developed.

**SOFTWOOD PLYWOOD DURABILITY**

The accelerated-aging procedure to evaluate the durability of exterior-type softwood plywood was developed empirically in the early 1930's and is still in use today. However, an additional procedure has since been developed which is less time consuming and more responsive to differences that may exist in adhesive cure.

One of the first exterior-type bonded-wood products to be developed was construction-grade softwood plywood. Specifications for its manufacture were described in U.S. Commercial Standard CS-45-38, issued in November 1938. The exterior-type product was expected to survive many years exposure to open weather in all areas of the United States. The quality control test procedure for this product was what is now known as the boil-cycle test (BDB) (A–5). After the broken specimens were dried, the percentage of wood failure over the fractured surface was estimated. High wood failure in this test was found to correlate with years of outdoor exposure without delamination, while shear strength values did not. Since it was later proved that phenolic adhesives were more resistant to hydrolysis and thermal degradation than wood, it became apparent
that the main function of the boil–cycle test as a quality control procedure was to apply a large amount of swelling and shrinking in a short time. It answered the question about whether or not a high quality bond had been manufactured--one that would resist the internal stresses that could be generated within the particular plywood configuration in question.

The boil–dry–boil test served the softwood plywood industry well during its early development. The test excluded the use of urea-formaldehyde adhesives which would not have been suitable for service environments where construction-grade materials were to be used. The test, as a quality control tool, effectively led to the production and use of a quality product which enjoyed increasing consumer acceptance and use. The boil–cycle test proved not to be the most ideal system, however, for it could not detect undercured bondlines of hot-pressed phenolic adhesives. The boil–cycle test also proved less than ideal for evaluating mismanufacture because of the lengthy time required to carry it out--over 24 hours. These problems provided support to those who advocated performance simulation tests and who reject boiling as unrealistic.

Later the boil–cycle test was supplemented with a vacuum-pressure-soak (VPS) (A–6) test which served the same function but used a lower temperature. This procedure could evaluate undercured bonds which in the past had been advanced in cure by the higher temperatures of the boil–cycle and be undetected. The VPS procedure also used wood failure as a measure of bond quality. The history of these developments was reviewed by Raymond (1975).

The fact that plywood shear strength lacked correlation with performance during outdoor exposure was due to the fact that the test for strength measured the rolling shear strength of the inner plies. These were low values compared with strengths of plies bonded parallel to the grain, and they reflected the quality of veneers rather than that of the bonds. While bonding may have reinforced the surfaces of the inner plies, this apparently was not detectable with relation to performance or within the normal variations of strength due to differences in grain, lathe checks, and other elements of wood structure contributing to shear strength.

The function of the adhesive bond in plywood was to transfer stress between adjacent plies whose grain directions were at right angles to one another, and to resist the internal stress development that takes place with moisture content changes. The quality control tests of BDB and VPS simply developed the maximum internal stress the product was able to generate, and the amount of wood failure was a measure of the area of bond capable of resisting that stress.

This discussion about plywood has demonstrated that tests developed for one panel product such as plywood cannot be directly applied to the durability evaluation and quality control of another, such as a composite panel. The development of composite panels with veneer faces on cores consisting of particles, flakes, or strands posed new problems in evaluating bond quality in terms of expected performance.

COMPOSITE PANEL DURABILITY

With the development of composite panels that combined veneers with particle-type cores, the need arose for quality control tests for the manufacturing process. The core material did not lend itself to any estimate of wood failure as a measure of bond quality. Some other approach was needed. The American Plywood Association (APA) conducted an extensive study evaluating a variety of composite panels by several laboratory test procedures and compared the results with those following outdoor exposure of the same materials (Raymond 1975) (A–7). The results after 1 year suggested that a suitable test might consist of exposing small specimens to daily cycles of soaking under vacuum and drying at moderate temperatures. The specimens would then be examined for delamination. One hundred percent of all specimens should survive 4 cycles or 2 days exposure to assure outdoor durability well in excess of 1 year. Here again, the conditions of exposure create high internal stresses and the extent of delamination measures those areas where bonds were incapable of resisting the stress. The delamination measurements can readily be made if there is a distinct line of demarcation to probe, but it cannot be applied to fiberboards, flakeboards, strandboards, or waferboards where such a distinct bondline does not exist.

PARTICLE-, FLAKE-, WAVER-, OR STRANDBOARD DURABILITY

The development of new wood–based panel products from wafers, flakes, or strands for exterior applications resulted in renewed efforts to develop improved accelerated-aging procedures. These attempts took place in a number of different laboratories using a variety of approaches to the problems under investigation. A review of these efforts is particularly pertinent to the situation as it exists today in the waferboard and flakeboard industries.

Waferboard originated in the United States in 1954 through developments by J. D'A. Clark. The first plant was built in Idaho in 1956, and commercial interest in waferboard increased as a result of further developments in Canada (J. D'A. Clark 1980; P. Vajda 1980). The product resulting from these developments used a powdered phenolic resin at a level of approximately 3 percent ovendry weight of wafers.

Later a flakeboard development was carried out by the U.S. Forest Service to stimulate the use of forest residues. Performance criteria were set up using the best engineering judgment available to produce a product that could possibly serve the same end uses currently satisfied by construction-grade plywood. Target properties for the Forest Service structural flakeboard approached those of construction-grade softwood
plywood. The results of the structural flakeboard development program were summarized in a general technical report (USDA 1978). The product was characterized by the use of liquid phenolic adhesive at a level of approximately 5 to 6 percent.

The major efforts in the development of structural flakeboard used phenolic resin binders, because a highly durable, waterproof bond was desired. Even with the selection of a heat and hydrolytically resistant adhesive, there was still a need to demonstrate that the resulting product would perform as intended. There was also the need for developing a quality control test, but the performance-oriented question was addressed first.

**Accelerated-Aging Tests**

Based on the premise that the major degrading influence affecting phenolic-bonded flakeboard would be internal stress development, the procedures selected for evaluating this factor consisted of multiple cycles of boiling and drying, and also vacuum-pressure soaking with intermediate temperature drying. A variety of flakeboards was subjected to these procedures along with samples of plywood and solid wood. The resulting changes in bending strength and stiffness under soaking and drying conditions so severe that even highly resistant solid lumber and marine-grade plywood, whose performance is well regarded, suffered appreciable losses (Baker and Gillespie 1978; River, Gillespie, and Baker 1981).

Other investigators also found cyclic exposures useful for evaluating exterior-type panel products. Beech (1973); Beech, Hudson, Laidlaw, and Pionion (1974) advocated the V313 three-cycle procedure (AFN 1972) (A–9). The change in bending strength, bending stiffness, internal bond, and thickness swelling correlated well with the property changes after 2 years weathering.

Lehmann (1968) evaluated a number of exterior-type particleboards by the ASTM D 1037 aging test, by the West Coast Adhesive Manufacturer’s Association (WCAMA) 6-cycle exposure (A–10), and by a vacuum-pressure soak and dry (VPSD) 5-cycle procedure (A–11). In all cases tests were carried out after specimens were conditioned to 65 percent relative humidity (RH). It was found that VPSD exposure test results provided the best correlation with 2 years of natural weathering.

In a later study, Lehmann (1977) evaluated a number of commercial and laboratory-prepared Particleboards, flakeboards, waferboards, and fiberboards using the ASTM D 1037 aging procedure, the VPSD exposure, a spray–dry exposure from ASTM D 2898, (A–12), and a 2-hour boiling with testing both wet and dry. The D 1037, VPSD, and D 2898 Procedures were repeated with specimens removed for test after 1, 2, 3, 6, 12, and 24 cycles. However, no consistent correlation was found between results of accelerated aging and those from 1 year of natural weathering. The results led Lehmann to recommend two types of tests: (1) a rapid test of a vacuum-pressure soak, boiling, and drying, and (2) a cyclic wetting and drying using moderate temperatures rather than boiling followed by high-temperature drying.

**Tests in Simulated Service Environments**

There are certain important end-use properties of wood-based panel products that can be measured only through simulation of service environments rather than with the use of conditions that might be unrealistic. Even though the temperature and moisture conditions selected are within the range found in service environments, the procedures can be considered as accelerated aging because the cycles selected usually take place more frequently than normal, and the conditions range between extremes rather than changing moderately. The objective is usually the determination of how much change would occur in a product with regard to bending strength and stiffness, creep, or dimensional stability when subjected to simulated service environments.

McNatt (1982) investigated the effects of cyclic humidity exposure on the bending strength and stiffness of wood-based panel products as reported by different investigators. The nine studies evaluated provided indications that: (1) UF-bonded particleboards were affected more by cyclic exposures to changes in humidity than were those bonded by phenol-formaldehyde adhesives, (2) cyclic humidity exposures are more severe at elevated temperatures, and (3) for a given temperature, cyclic humidity conditions will produce comparable results that depend on total exposure time rather than the number of cycles when essentially equilibrium moisture content is achieved after each humidity change.

McNatt and others (Armstrong and Grossman 1972; McNatt and Hunt 1982; Lehmann, Ramaker, and Hefty 1975; McNatt and Superfesky 1982; Schniewind and Lyon 1973; and Tyne 1978) evaluated creep deflections when particleboard and hardboard were subjected to cyclic humidity while under load at ambient temperature. It was found that creep deflections were as much as five times greater under cyclic humidity conditions than when humidity was held constant. It was recognized that cyclic humidity at a constant temperature is not a "real-life" exterior exposure condition where a decrease in humidity is usually accompanied by an increase in temperature and vice versa. It was also found that cyclic humidity–constant temperature exposure was considerably more severe for creep under load than when exposed to an exterior exposure where protection was provided against direct exposure to sunlight and precipitation.

**DURABILITY TESTS VERSUS QUALITY CONTROL TESTS**

Test procedures designed to evaluate durability are different from those used to control quality of manufacture. The same test procedures do not serve both purposes.
All of the multiple-cycle exposures have as their main objective the demonstration whether or not a board product will perform as desired for many years in direct weathering. They are time consuming, labor intensive, complicated, and require numerous large specimens and commensurate equipment capacities. There is a basic difficulty involved in the development and use of such test procedures. First of all, there is a desire for test procedures that simulate actual long-term service conditions. But when new products are to be evaluated, there is little choice but to use accelerating procedures. In contrast, there is a need for quick and inexpensive test procedures to detect the adverse effects of product mismanufacture. The lengthy cyclic tests are needed to qualify new products for certain end uses, while the quick and nonsimulative type are required for quality control purposes during product manufacture. In addition, test procedures have been developed for purposes other than those mentioned above. These include tests to evaluate adhesive durability properties; tests to exclude the use of adhesives already known to be unsuitable for certain uses; tests designed to include specific materials known to be satisfactory; tests to simulate service condition effects on dimensional stability; tests to detect creep behavior in changing environments, etc. Many of these tests are misused, the results of others are misinterpreted, or the results may be viewed with overexpectations.

These conflicts or philosophical difficulties have been discussed by Carroll (1978, 1980). The major heading for these articles which states, "We still don't boil houses," suggests, therefore, that it is improper to boil primary building materials when their usual service conditions are not reproduced. This, of course, refers to the boil–dry–boil cycle test used to evaluate construction grades of softwood plywood (PS–1–1974). Carroll traces the history of test development for wood-based panel products and discusses the different philosophies of approach and the inconsistencies that arise.

Carroll's second article (1980) extended the discussion to consider the more profound differences that exist in the testing of structural-type particleboards. He compared the particleboard standards and specifications developed in Europe with those used in North America. Differences exist in the expected performance. The Europeans favor a board with 8 to 10 percent resin and springback below 8 percent after cyclic aging, while the Canadian waferboard contains only 2 to 3 percent PF resin binder and shows 30 to 35 percent springback after boiling and reconditioning. All of the specifications contain test procedures to measure a moisture resistance or simulated weathering resistance. They all contained test criteria that define the limitations that are permitted to take place in springback, internal bond, or bending properties after specimens have been subjected to certain laboratory–controlled exposure conditions.

The U.S. standard for particleboards (NPA 1979) uses the 6-cycle accelerated-aging test described in ASTM D 1037 (1981). Bending specimens are reconditioned prior to test, so 3 to 4 weeks are required to complete the data collection. The French CTB–H standard (1975), and the British standard (BS 5669, 1979) use the V313 procedure with reconditioning prior to test. The time required to complete is 4 to 5 weeks. In contrast, the German and Canadian standards use a 2-hour boil test. The German standard, DIN 68763 V100 (1973) (A–13) relies on testing for internal bond in the wet condition. This requires bonding of gripping blocks to the faces of the specimens before soaking and boiling, therefore, the test requires approximately 6 hours. The Canadian standards (CSA 1978) (A–14) describe the use of bending specimens for a 2-hour boil and 1-hour soak in cool water before testing wet for bending strength. Elapsed time of test is only 3 hours. Of these procedures only the 2-hour boil test of the German and Canadian standards approaches the short time conditions required for an acceptable test for controlling mismanufacture of a product. These two standards also require the use of a PF resin adhesive which automatically establishes a high level of hydrolysis resistance for the system. The accelerated-aging procedures in the U.S., French, and British standards, which do not specify the adhesive type, are totally unsuitable for control of product mismanufacture because of the slow nature of the cyclic procedures, and the time spent reconditioning specimens to EMC conditions.

Efforts have been made to develop such rapid quality control tests, particularly in Canada. Shen (1977) summarizes the work on developing a proposed rapid accelerated-aging test for exterior waferboard which involved the measurement of torsion shear strength. The specimen size was 25 mm × 25 mm (1 in. × 1 in.). The specimens were boiled for 20 minutes before cooling in water and measured wet for shear strength by a torsion technique. These torsion shear values were shown to be related to other strength properties of particleboards (Shen 1971). This system eliminated the bonding of gripping blocks to specimens and required standard internal bond tests, reduced the size of specimens and the time of exposure, and made it possible to test many more specimens rapidly and accurately. This test procedure has not been incorporated in any standards or specifications so far but continued use and evaluation should demonstrate its full potential for the purpose of controlling mismanufacture. The technique has been applied to the evaluation of composite panels (veneer–overlaid core boards) with encouraging results (Countryman 1979). Continued evaluation of accelerated torsion shear tests on small specimens should probably be carried out on boiled specimens and also those subjected to vacuum–pressure soaking, as suggested by Clad (1979).

The need for a number of different tests designed for specific purposes has also been advocated by Gressel (1980, parts 1, 2, 3) (A–15). Gressel carried out an extensive review of the problems associated with evaluating the durability
DESIGNING FOR DURABLE BONDED-WOOD ASSEMBLIES

Another approach to durability evaluation is to use a specified series of tests that supply information to architects or design engineers for designing safe structures.

Adhesives have been used in truly structural applications for many years. A design strategy for using adhesives in such applications was not needed since joints always failed with high wood failure. The properties of the adherends governed the design, and the adhesive being stronger and more durable than wood provided a stress-transfer function.

In recent years, adhesives less strong, less durable, and more susceptible to creep than wood have been used in assembly bonding for structural applications. Examples are the use of elastomeric mastic adhesives for bonding plywood to floor joists during onsite construction, and the application of polyvinyl acetate adhesives for bonding panels in mobile homes to improve racking resistance during over-the-road transportation. These developments raised new concerns about the use of adhesives in structural applications, and about how new assemblies could be designed with adhesives whose properties might control the ultimate Performance of the assembly.

A technique for determining design stresses for bonded joints based on the already accepted method for developing design stresses for wood was proposed by Lewis (Gillespie and Lewis 1972). For wood, the values for the mechanical properties of small, clear wood specimens are converted to design values by a series of reduction factors. These adjust the clear wood situation to the real-life situation with wood having grain directions, knots, etc. The proposed equation for design stress of adhesives was:

\[
\text{Design stress} = \frac{\text{Mean stress} \times \text{Variability factor} \times \text{Exposure condition factor} \times \text{Quality factor} \times \text{Duration of load factor} \times \text{Safety factor}}{100}
\]

A similar equation can be applied to shear modulus data to provide design values for the anticipated deformation of an assembly.

This concept was adopted and expanded by Krueger (1981) during an investigation of adhesives having potential for bonding structural elements in mobile homes or industrialized house manufacture. Mechanical properties of the adhesives were determined in shear and in tension before and after exposure to chemicals, moisture, heat, rodents, and microorganisms. Data were obtained for the effects of loads so that physical forces were evaluated along with the chemical effects of aging. This work also emphasized that a number of test procedures was necessary to characterize an adhesive's potential for long-term performance in structural applications. It also demonstrated one acceptable method for applying these data in situations which face design engineers. This design strategy was applicable to adhesives varying widely in mechanical properties, and could also be used for primary building materials containing adhesives, bonded joints, and bonded assemblies.

DEVELOPING SHORT-TERM ACCELERATED TESTS

Future needs for accelerated-aging tests might be met by yet another approach to procedure development which was suggested by investigators at the National Bureau of Standards.

The steps normally followed to develop tests that predict the durability of building materials have been outlined in a new ASTM Recommended Practice (ASTM E 632, 1978). The practice lists the degradation factors affecting the service life of building materials and outlines a 16-step procedure for developing short-term tests that evaluate these influences. The objective of this practice is to lead to greater uniformity in the approaches to service life and durability predictions so that increased confidence in the predictions will grow through its use.

The rapid developments that have taken place in space technology have emphasized the engineering concept of reliability of materials. These concepts are based upon the probability that a material or device will perform as intended under the planned service conditions and for the expected period of time. Future studies dealing with the development of methods to predict durability should involve the questions about
statistical significances of observed differences in material behavior, and also they should be approached from the statistical viewpoint of reliability theory (Frohnsdorff and Masters 1980).

**CONCLUSIONS**

The past studies of the durability of building components and materials discussed in this paper have resulted in the development of a wide variety of test procedures and practices. Many of these procedures are misunderstood and some of them misused. There are several reasons why such a situation exists. We all have difficulty understanding each other when words like durability, weatherability, serviceability, performance, and service environments mean somewhat different things to different investigators. This condition is aggravated further upon translating the meanings of words from one language to another. Also, investigators have different philosophies of approach to durability assessment, ranging from those who insist on simulating service conditions without exceeding their intensity to those who are willing to exaggerate the levels found in end-use environments well beyond natural conditions. In addition, investigators often overlook the historical background information pertinent to the development of a specific procedure. This information may not be readily available, or the original purpose for the development may be obscure. A test procedure is often borrowed for use with a new material or for a new purpose. It is more expedient to attempt such a transfer of technology rather than develop new methods.

In cases where new standards and specifications have been written for products entering commercial reality, suitable test procedures for control of mismanufacture had not been developed as yet. The authors of such documents had no alternative but to fall back on the test procedures used during product development as the only methods in which a reasonable level of confidence could be generated and agreed upon by producers, users, and the general interest people involved. The development of suitable quality assurance tests was often neglected. Common misunderstanding about short-term tests for product durability became further compounded by misuse of a procedure and the inevitable misinterpretation of results.

There is a need for several different tests to clarify all the questions relating the new materials' response to a specified end-use situation. There is a continual need for new test procedures developed for new materials and for new purposes so that pertinent durability questions can be answered more rapidly and accurately. There is a particular need for the development of new quality assurance tests to reduce the possibility of mismanufacturing new bonded wood products. There is a need to apply new approaches such as those based upon reliability theory so that improved predictions can be made.

An improved understanding of existing test procedures, a reduction in conflicts of outlook, and the development of new procedures with well-designed purposes based upon well-established fundamental principles will provide the confidence needed for the successful development and use of our future building components and materials.

**LITERATURE CITED**


Gillespie, R. H.

Gillespie, R. H.

Gillespie, R. H.

Gillespie, R. H., and B. H. River

Gillespie, R. H., and B. H. River

Gillespie, R. H., and W. C. Lewis.

Gray, G. C.

Gressel, P.

Gressel, P.

Gressel, P.


Hobbs, R. B.


Techical Association of the Pulp and Paper Industry.

Tyne, J. R.

USDA, Forest Service

Vajda, P.

Voluntary Product Standard PS-1-74.


West Coast Adhesive Manufacturers Association Technical Committee.

West Coast Adhesive Manufacturers Association Technical Committee.

W. J. Barrow Research Laboratory.

APPENDIX

A-1 (ASTM D1037)
6 cycle
Spray: 93°C, 3 hr.
Freeze: -12°C, 20 hr
Thaw: 100°C, 3 hr.
Spray: 93°C, 3 hr.
Dry: 100°C, 18 hr.
Repeat 6 times
Recondition prior to test

A-2
(Jessup, Weber, & Weissberg 1941)
Dry: 65°C (149°F), 3 hr.
Soak: Room temperature, 3 hr.
Freeze: -12°C (10.4°F), 18 hr
Repeat 25 days, or 600 hr.

A-3 (FPL 1963)
Adhesive Durability Exposures
Continuous:
Water soak -- room temperature
Condition 80°F - 97% RH
Condition 80°F - 65% RH
Condition 158°F - 20% RH
Condition 158°F - 60% RH
Condition 200°F - 20% RH

A-4 (FPL 1963)
Adhesive Durability Exposures
Cyclic:
1. Water soak -- room temperature, 2 days
Dry: 80°F - 30% RH, 12 days
2. Condition 80°F - 97% RH, 2 weeks
Condition 80°F - 30% RH, 2 weeks
3. Condition 80°F - 65% RH, 16 hr.
Condition 158°F - 20% RH, 8 hr.
4. Condition 80°F - 65% RH, 16 hr.
Condition -20°F, 8 hr.

A-5 (PS-1 1974)
Boil, 4 hr.
Dry: 63 ± 3°C (145 ± 5°F), 20 hr.
Boil, 4 hr.
Cool in water
Test wet

A-6 (PS-1 1974)
Submerge in cold tap water
Vacuum, 25 in. of mercury, 30 min
Pressure, 65-70 psi, 30 min.
Release pressure
Test wet

A-7 (Raymond 1975)
Composite Panel
APA, 1 in. x 5 in. specimen
Water soak 66°C (150°F)
Vacuum, 15 in. of mercury, 30 min
Dry: 49°C (120°F), 6 hr.
Measure delamination of bondline
Failure: 1/4 in. deep, 1 in. long

A-8 (Baker & Gillespie, 1978; River, Gillespie, & Baker 1981)
Submerged boiling water, 10 min.
Dry: 107°C (225°F), 3.75 hr.
Vacuum pressure soak, 1 hr.
Dry: 82°C (180°F), 23 hr.
A-5 (Beech 1973; Beech, Hudson, Laidlaw, & Pinion 1974)
V-313--3 cycle

Water soak, 20°C (68°F), 3 days
Freeze, -12°C (10°F), 1 day
Dry, 70°C (158°F), 3 days
Condition 65% RH

A-10 (Lehmann 1968)

Soak, 21°C (70°F)
Vacuum, 27 in. mercury, 20 min.
Boil, 3 hr.
Dry, 105°C (220°F), 20 hr.
6 cycles

A-11 (Lehmann 1968)

Dry, 105°C (221°F), 22 hr.
Submersion in water 21°C (70°F), 30 min. & 25–30 in. of mercury vacuum
Submersion in water 21°C (70°F) & 75 psi pressure, 60 min.
5 cycles
Conditioned to 65% RH

A-12 (ASTMD2898)

Spray water, 21°C (70°F), 4 hr.
Dry, heat lamps, 66°C (150°F), 4 hr.
Repeat spray
Repeat dry
Rest, ambient temperature, 3 hr.

A-13 (DIN 6873, 1973)

Soak, 1–2 hr.
Boil, 2 hr:
Cool in water, 1 hr.
Test I8 wet

A-14 (CSA 1978)

Boil, 2 hr.
Cool in water, 1 hr.
Test bending strength wet

A-15 (Gressel 1980)

Performance Tests
1. Continuous Boil - 2, 6, 15 hr.
2. Cyclic Soak–Dry, V313, ASTM or WCAMA, 1, 3,
5 cycles

Suitability Tests
1. Cycle Between 95% and 65% RH, 20°C (68°F)
2. Creep Cycles Between 95% and 25% RH 20°C (68°F), each 48 hr., 20 cycles with quarter-point loads, 1/5, 1/4, 1/3, and 1/2 mean ultimate load

Figure 1.--Hypothetical treatment of shear strength data.